Electrostatic Accelerators

Joint ICTP-IAEA Workshop on Accelerator Technologies, Basic Instruments and Analytical Techniques

21 – 29 October 2019

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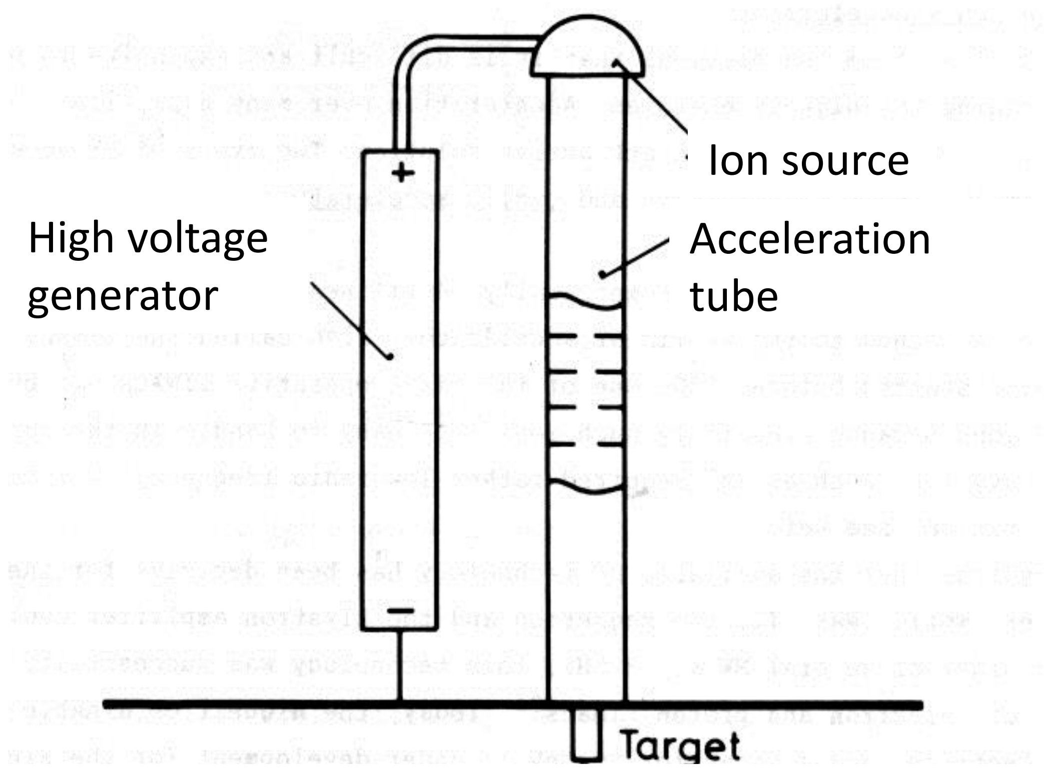
Overview of the lecture

1. Charging system to double or triple the voltage
2. Cockcroft-Walton accelerator
3. Van de Graaff accelerator
4. Tandem accelerator
5. Dinamatron / tandetron accelerator
6. Upgrade and maintenance at iThemba LABS electrostatic accelerators

Basic principle of an electrostatic accelerator

The principle of a electrostatic accelerator is shown in the figure below. The voltage from a high voltage generator is connected to the accelerating tube, and the particles are accelerated in one step through the tube, which is constructed as a long drift tube with a number of electrodes along the axis giving a rather uniform field distribution for acceleration.



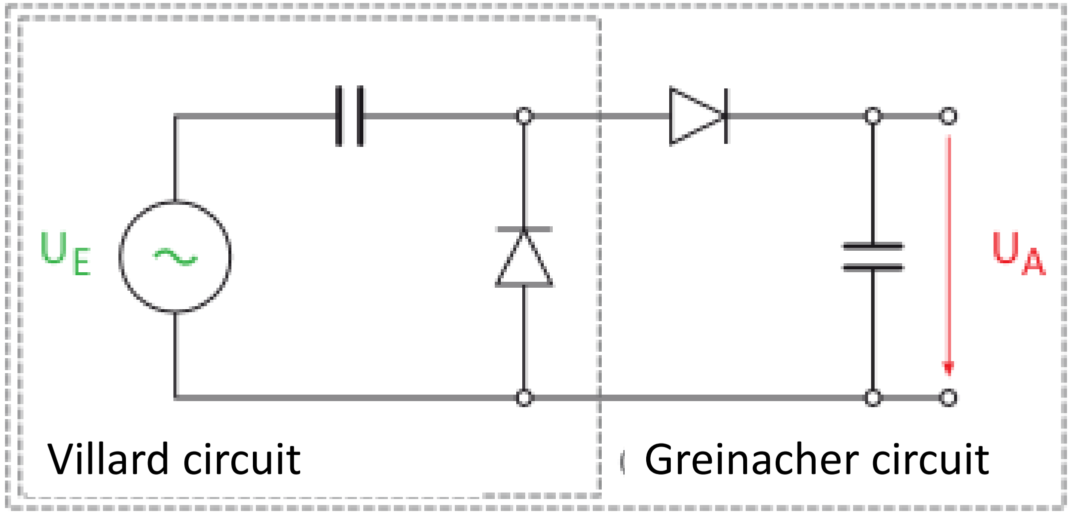
Basic principle of an electrostatic accelerator

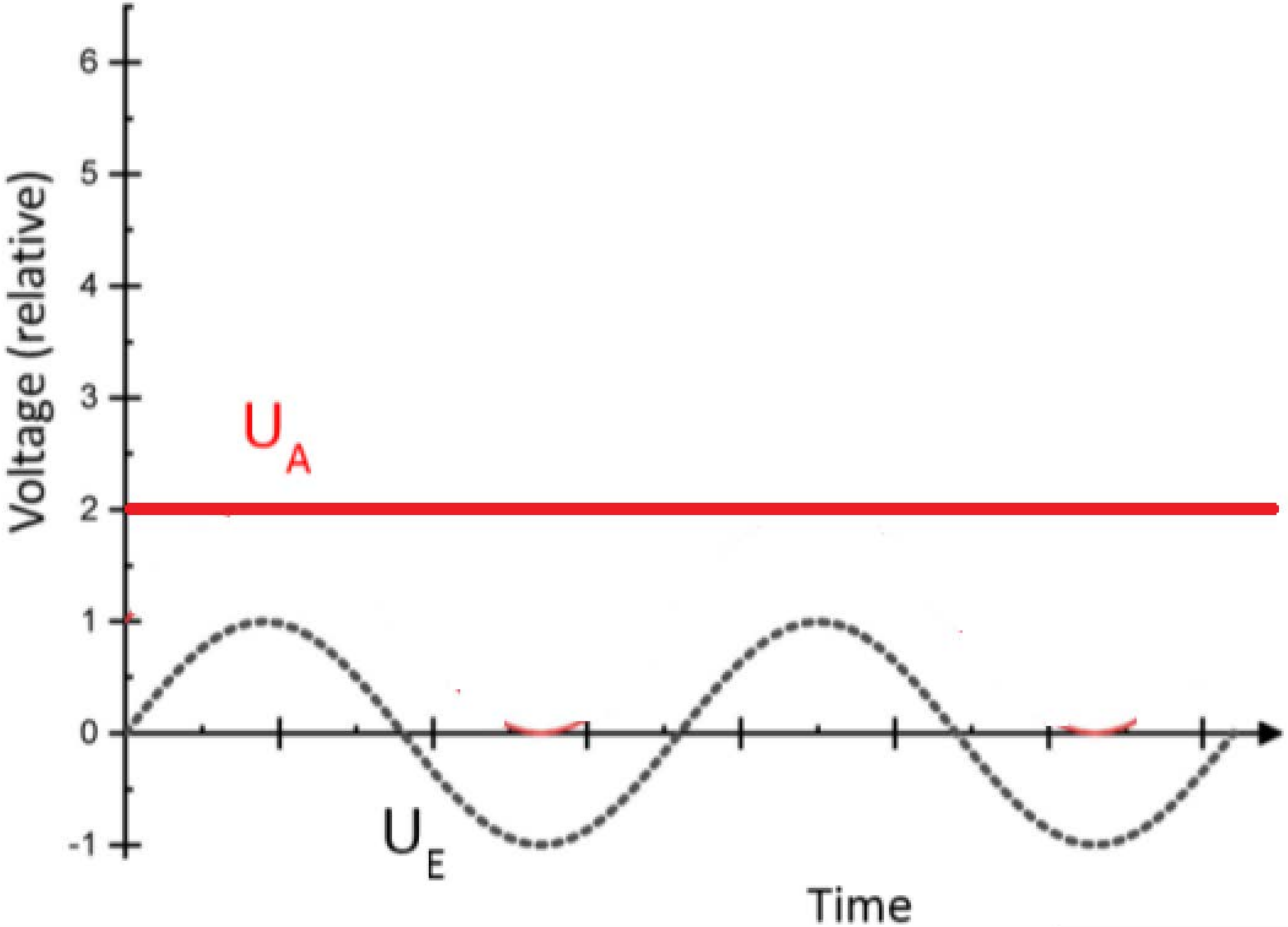
Electrostatic accelerators work by accelerating charged particles through a constant potential difference. If a particle has a charge q and mass m and move through a potential difference of V then it will gain a kinetic energy, $E_{Kinetic}$, of:

$$E_{Kinetic} = \frac{mv^2}{2} = qV$$

Cascade generator (Voltage doubler)

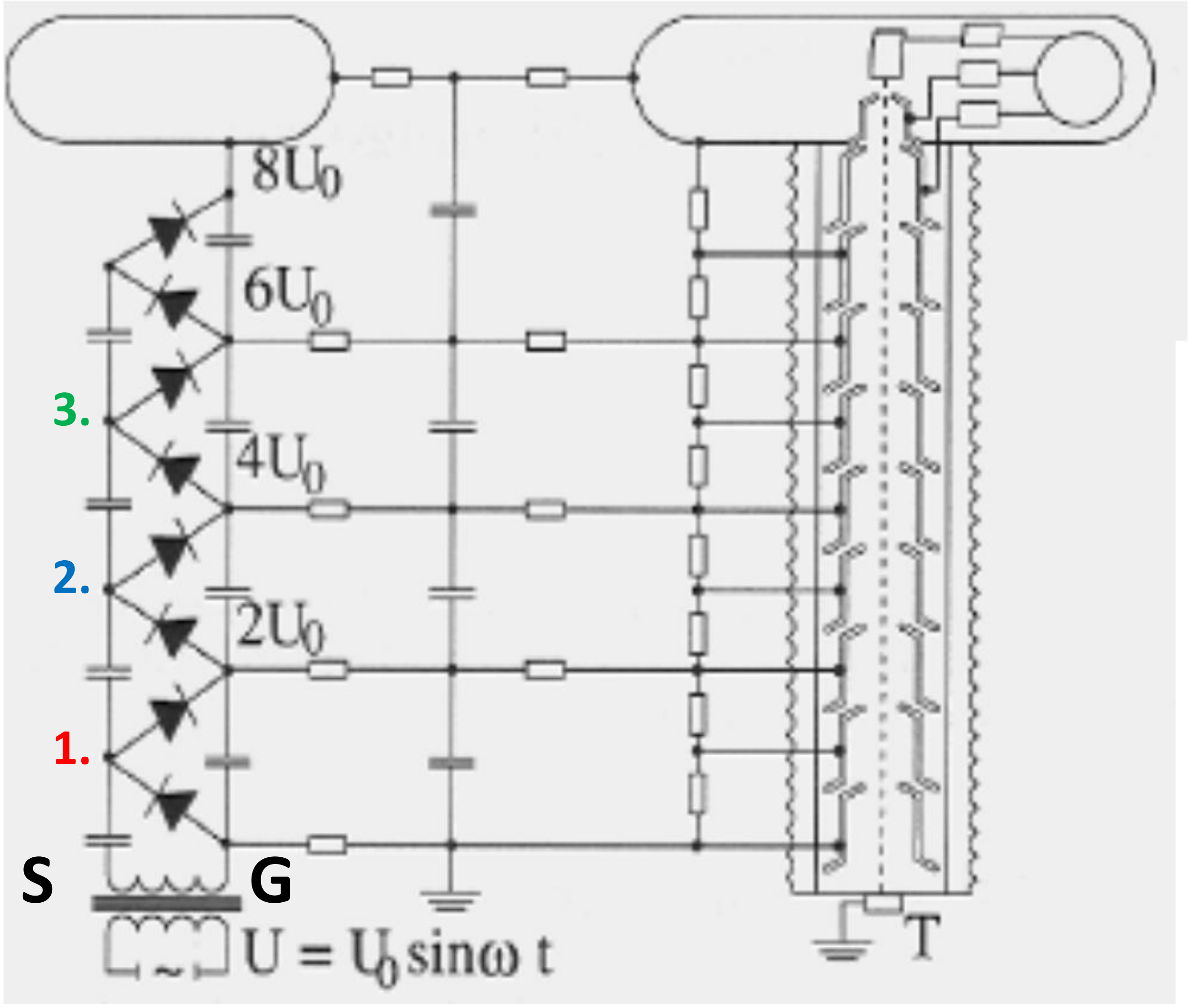
- Basis: Greinacher circuit



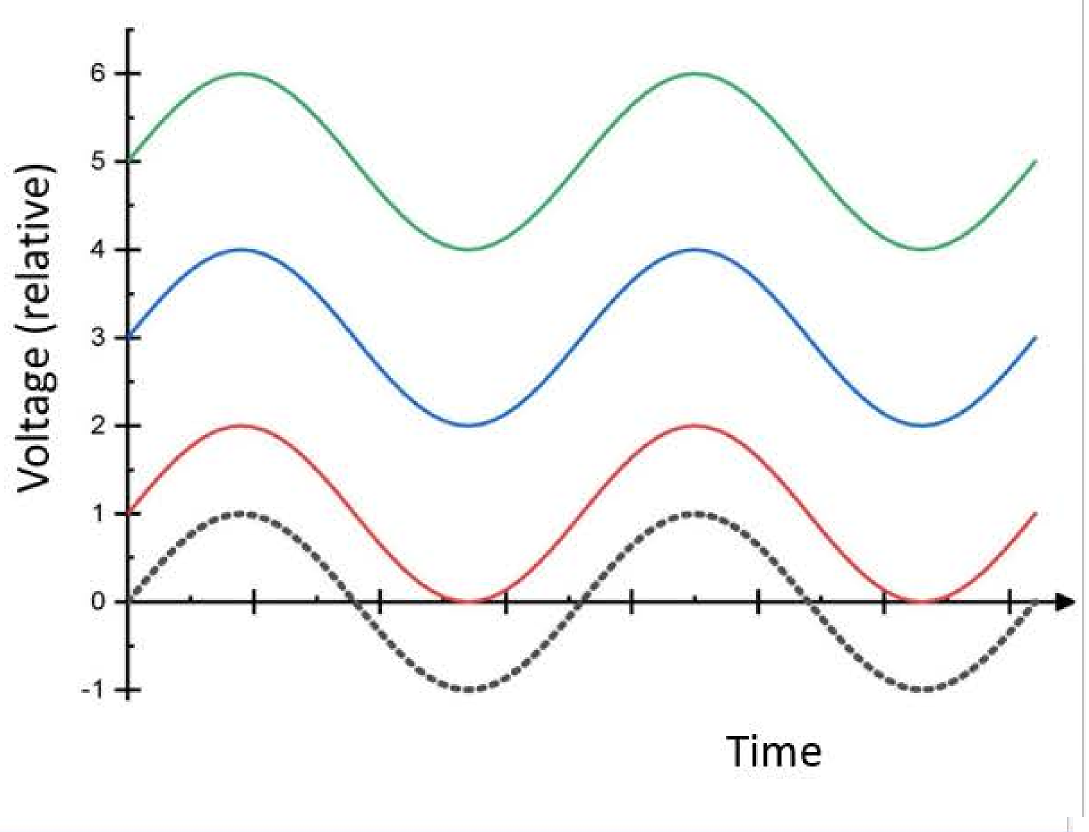


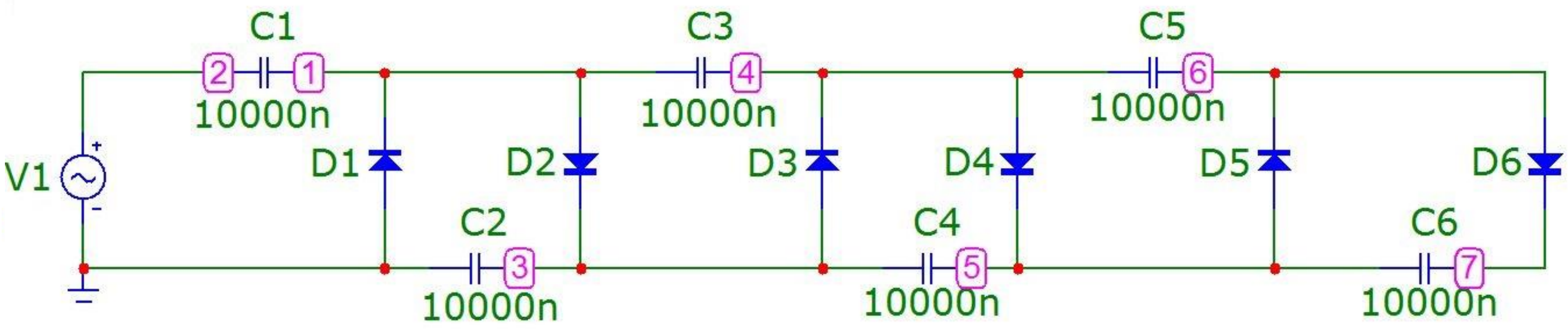
High votage multiplier cascade generator

- Basis: Greinacher circuit



- Cockroft, Walton 1937: 700 kV Nobelprize 1951: first to show that one element (lithium) could be artificially transformed or transmuted into another




C1
2
1
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C3
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C5
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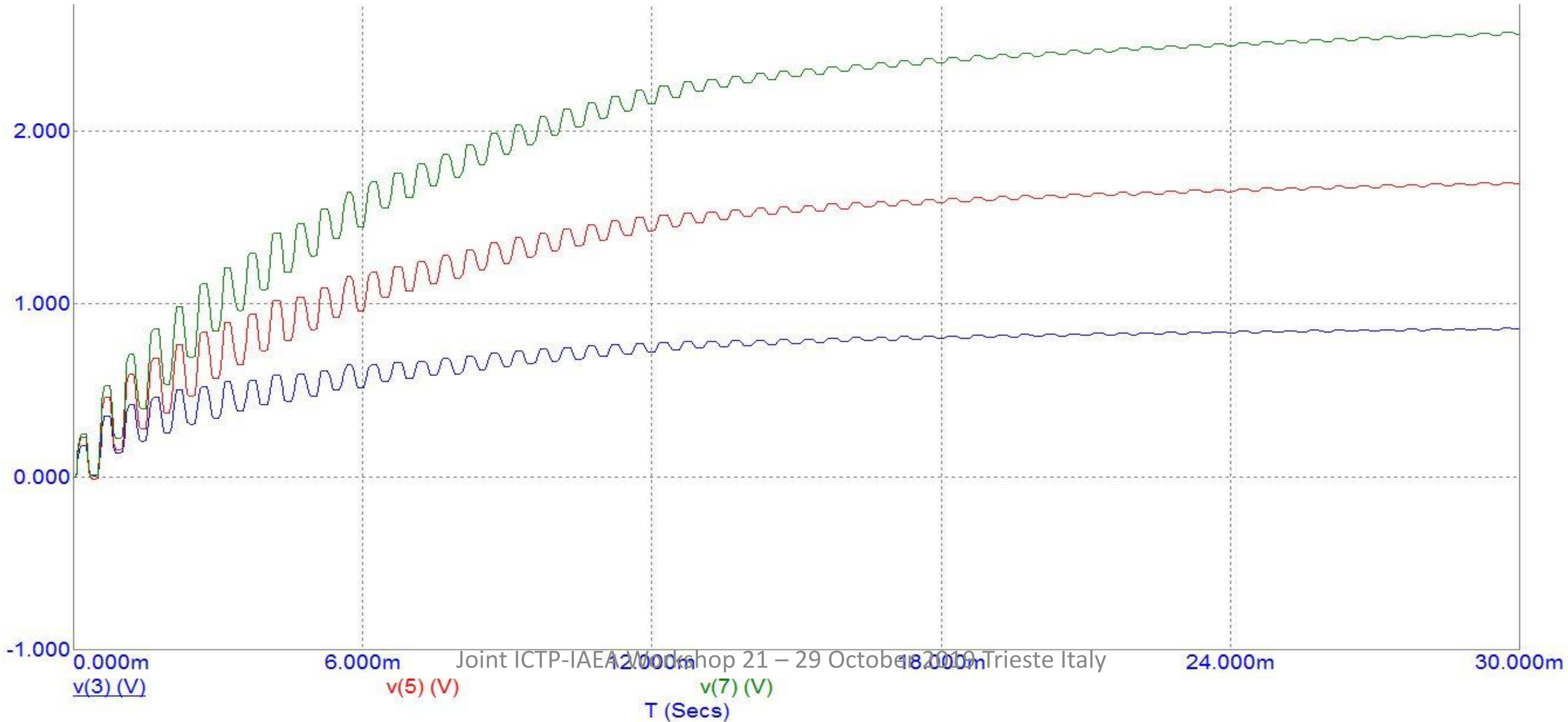
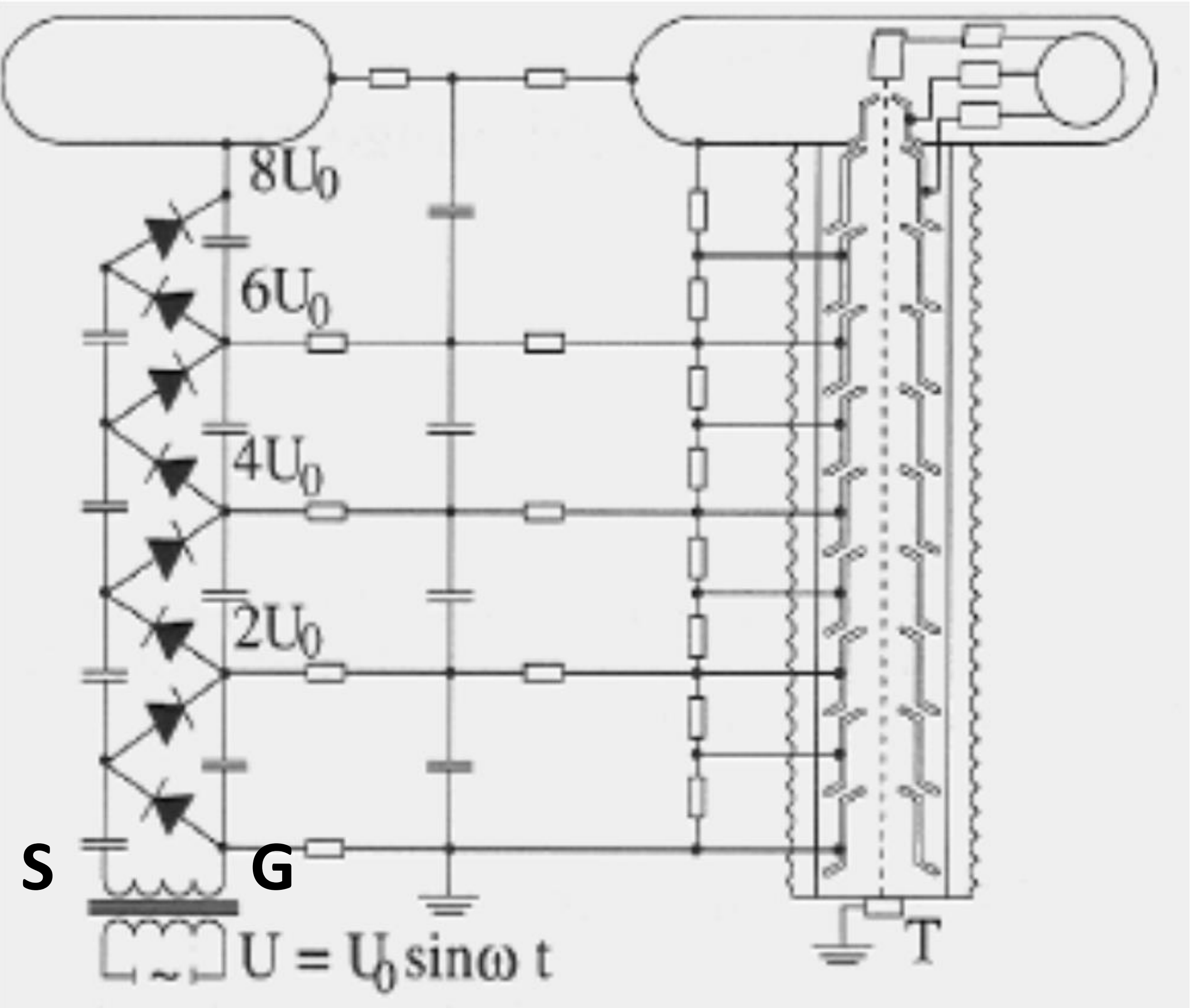

2.000
1.000
0.000
-1.000
0.000m
6.000m
12.000m
18.000m
24.000m
30.000m
v(3) (V)
v(5) (V)
v(7) (V)
T (Secs)

High votage multiplier, cascade generator

- Cockroft-Walton-Accelerator



$U = U_0 \sin(2\pi f\ t)$

- stationary: $U = 2\ n\ U_0$
- under load:
  - mean voltage drop ΔU
  - ripple δU

$$U_{total} = 2nU_0 - \Delta U \pm \delta U =$$

$$2nU_0 - \frac{I}{fC}\left(\frac{2}{3}n^3 + \frac{1}{4}n^2 + \frac{1}{12}n\right) \pm \frac{I}{fC} \cdot \frac{n(n+1)}{2}$$

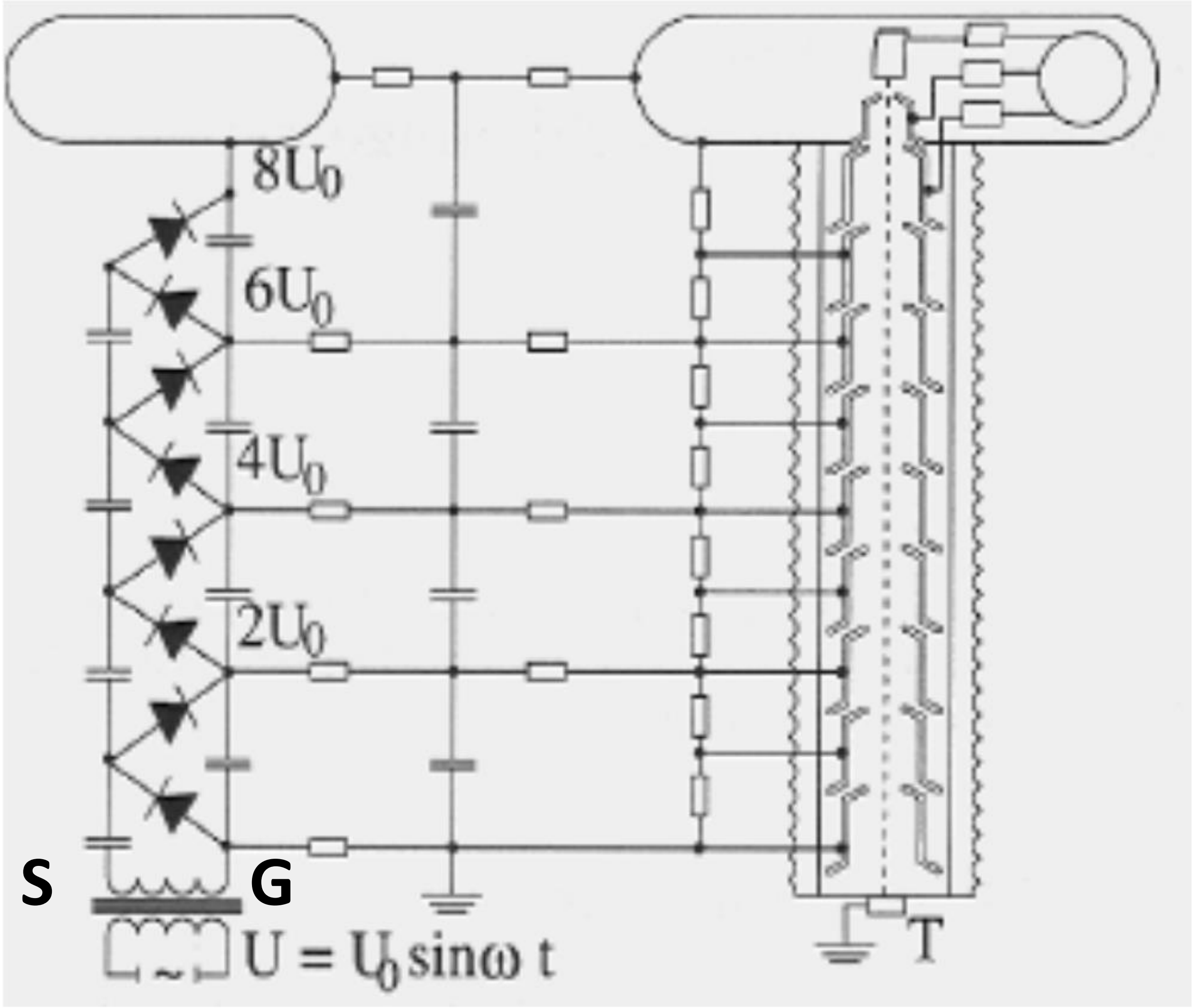
For small ΔU and small δU:

- high frequency of the alternating voltage
- high capacity C
- small number of steps n

- Typical values:
  - f = 0,5 – 10 kHz
  - C = 1 – 10 nF
  - n = 3 - 5

High votage multiplier cascade generator

- Cockroft-Walton-Accelerator



$U = U_0 \sin(2\pi f\, t)$

- High voltage terminal: particle source
- Rotating rods made of insulating material for drive and control
- Optical fibers for data transmission

Cacade generator

- Cockcroft-Walton at PSI, 870 kV
- Injector accelerator for injecting beam into the injector 2 cyclotron at PSI

Estimate of maximum voltage on high voltage terminal

Corona breakdown

Partial breakdown of the air occurs as a corona discharge on high voltage conductors at points with the highest electrical stress. Conductors that have sharp points, or balls with small radii, are prone to causing dielectric breakdown, because the field strength around points is higher than that around a flat surface. High-voltage apparatus is designed with rounded curves and grading rings to avoid concentrated fields that can cause breakdown of the high voltage.

- Eelectric field strength on the surface of a sphere
  = Voltage / Radius
- In dry air: breakdown at 3 kV / mm
  → at radius = 1 m: Umax = 3 MV
- In practice: only about one third of this value reached
- Solution: Pressure tank with insulating gas

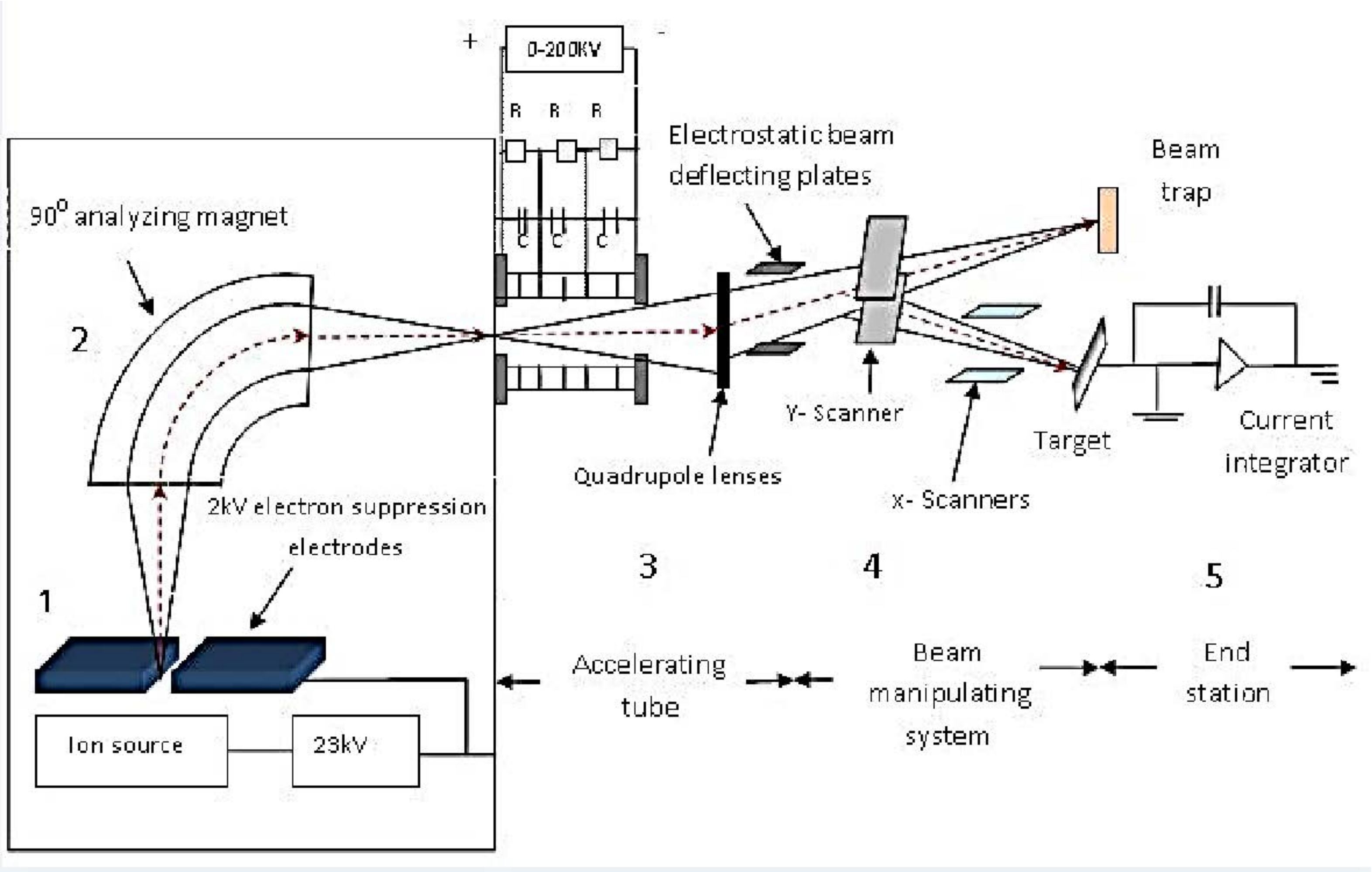
www.psi.ch

Terminal of iThemba LABS 6 MV CN Van de Graaff accelerato

Accelerator - Tube

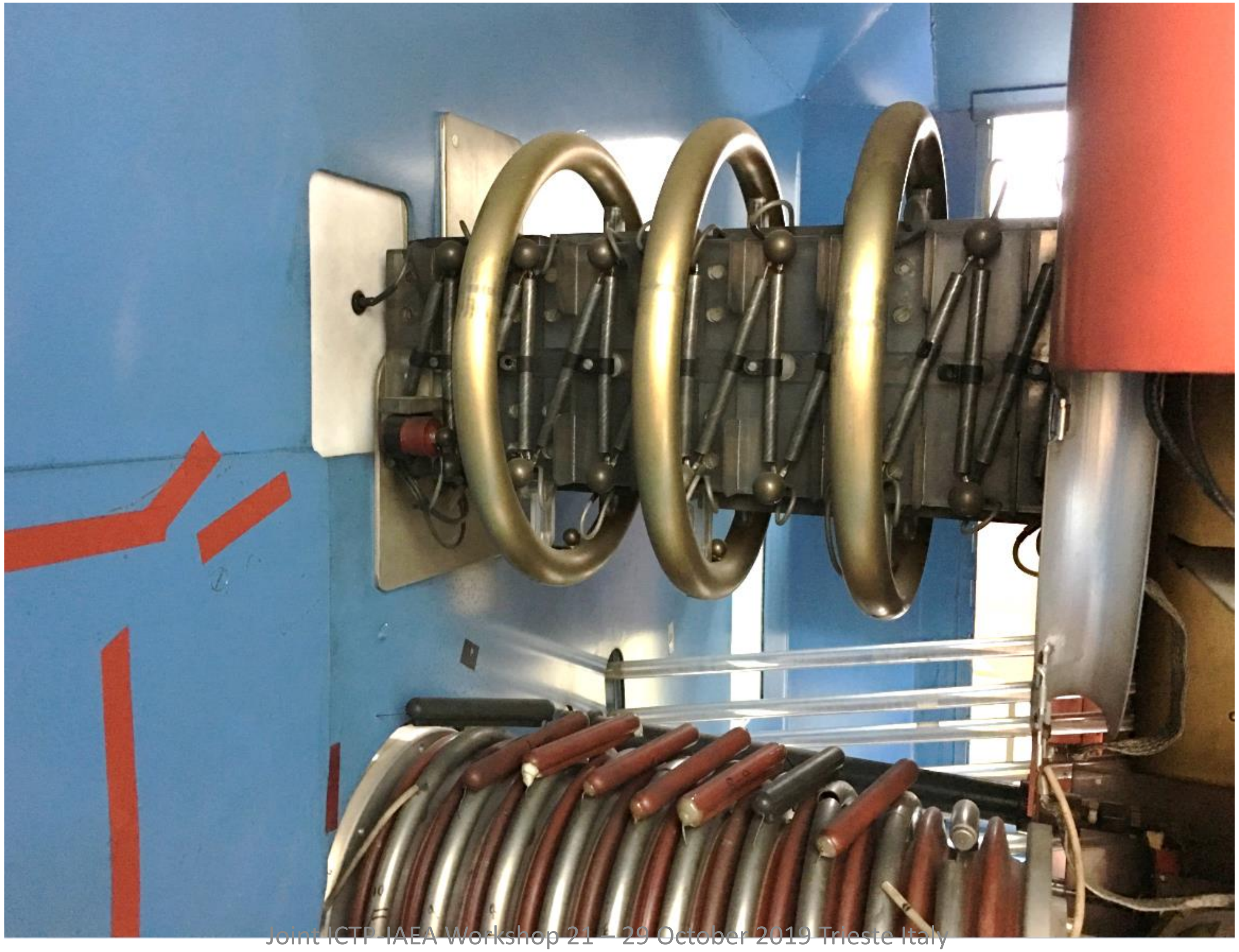
- Good vacuum in the accelerator tube to prevent flashovers due to residual gas (also minimizes particle losses)
- insulating rings with intermediate electrodes
- Intermediate electrodes connected via resistor chain to achieve a uniform voltage drop along the tube

Ion implanters (mostly of the Cockcroft Walton type)



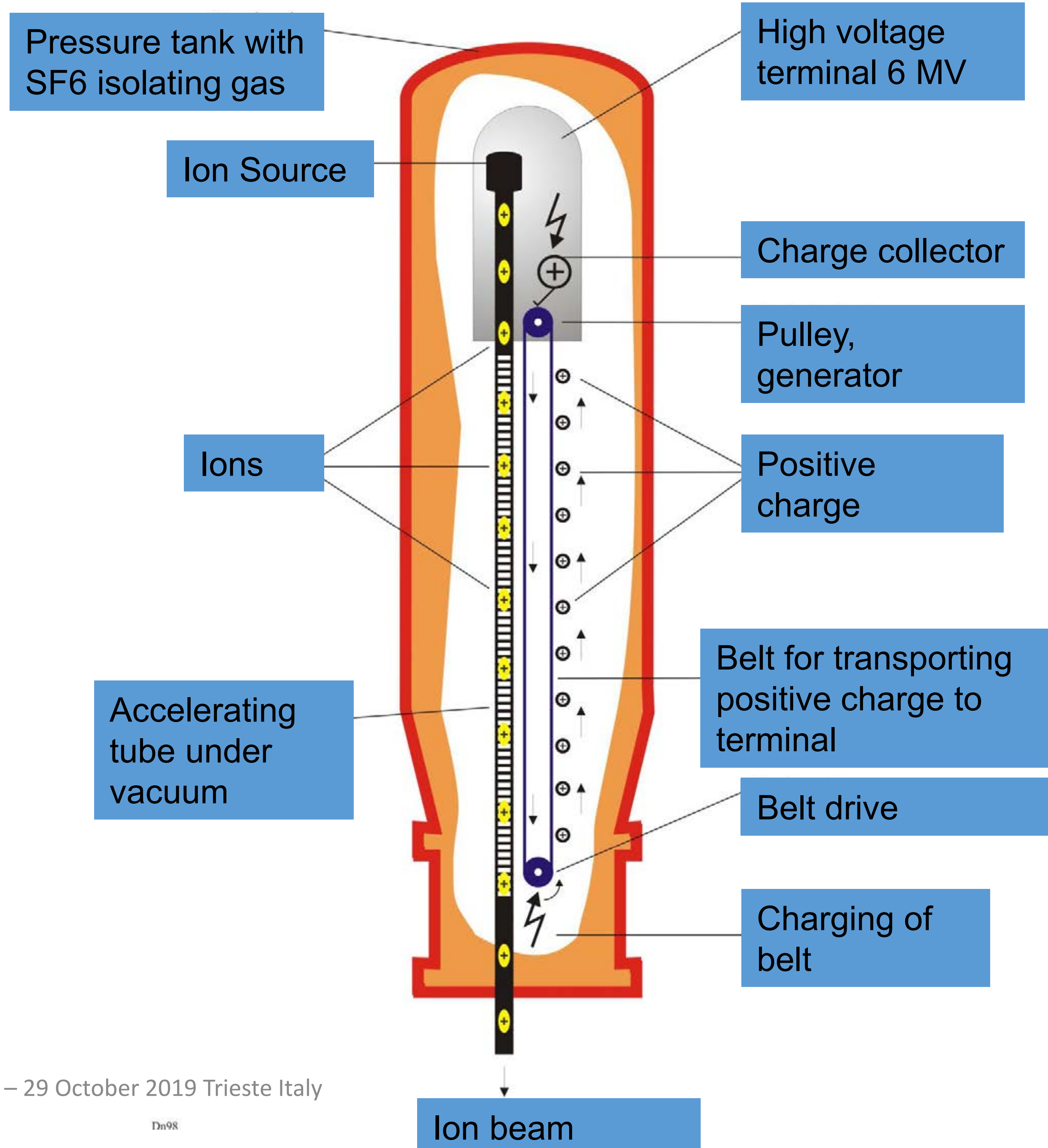
Ion implantation is a low-temperature process by which **ions** of one element are accelerated into a solid target, thereby changing the physical, chemical, or electrical properties of the target. **Ion implantation** is used in semiconductor device fabrication and in metal finishing, as well as in materials science research.

Part of the charging system top and the accelerator tube of ion implanter at iThemba LABS

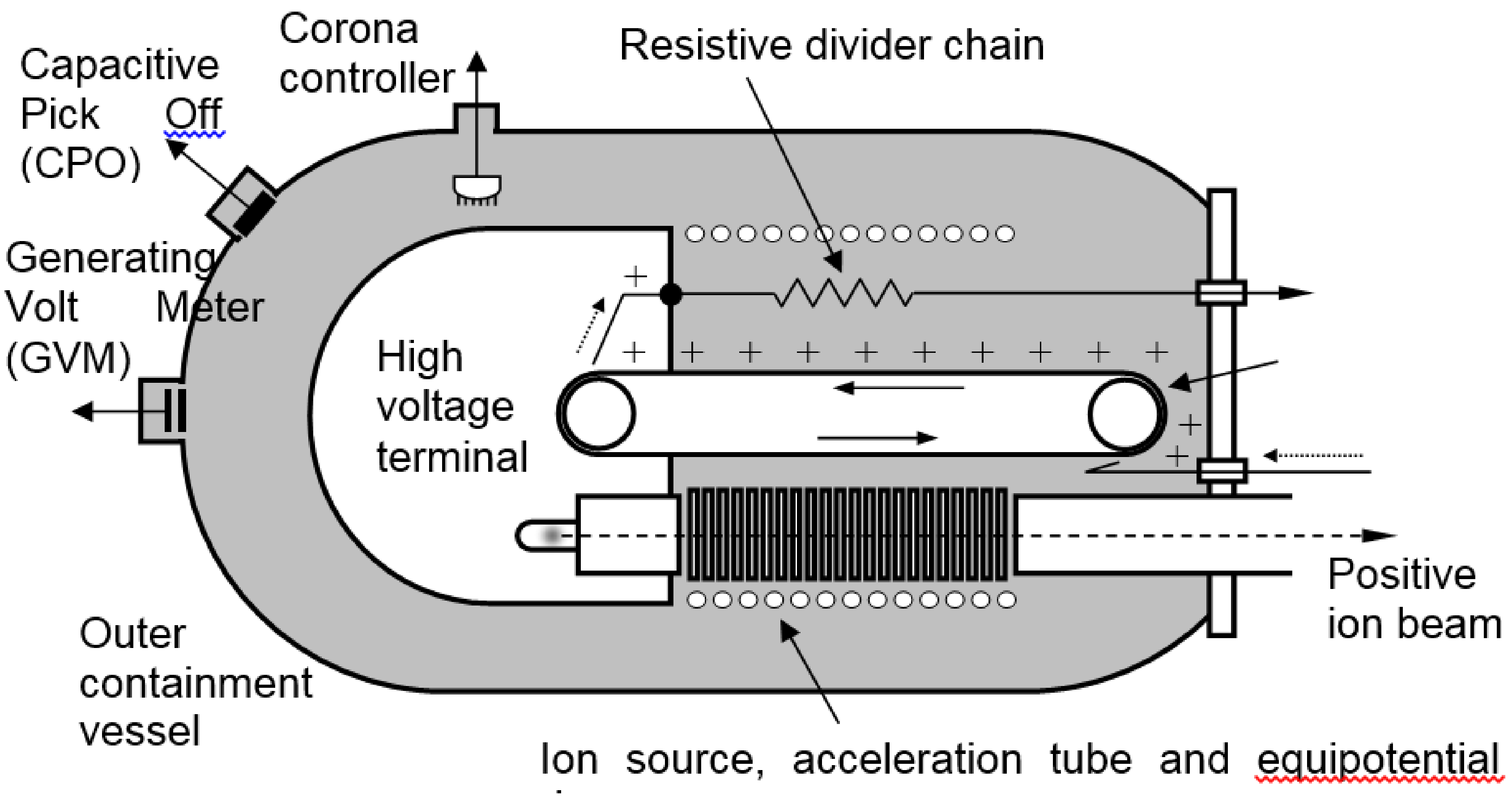


Van de Graaff Accelerator

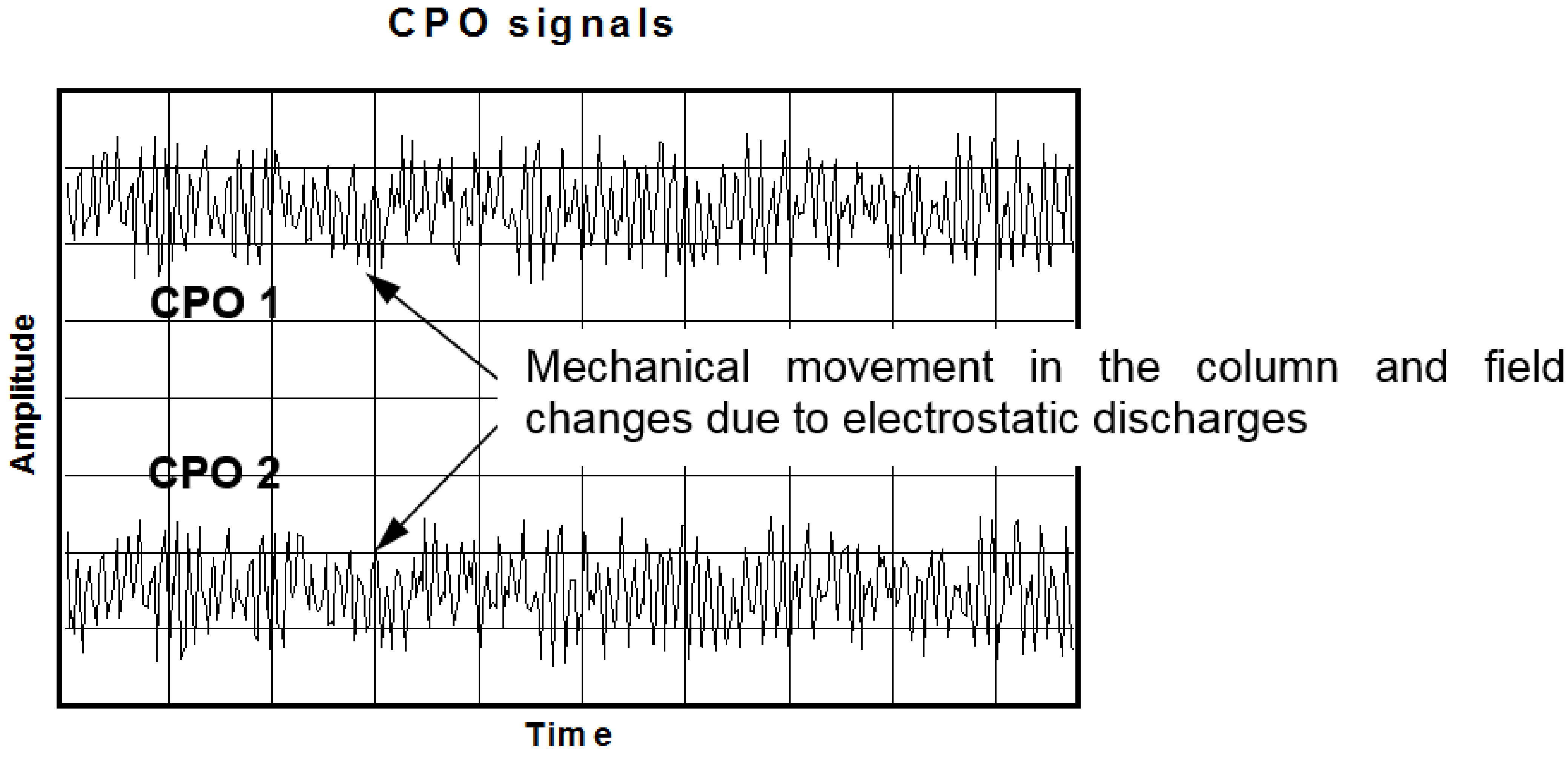
- Charge is sprayed on an insulating belt (field emission)
- Circulating belt:
  - transports charge to the high voltage terminal
  - drives generator in the terminal, so that energy is available for source
- Pressure tank for protection against flashovers
- Accelerating tube
- Charge collector
- Pulley, generator
- Charging of belt
- Belt drive



Controlling the maximum voltage on the high voltage terminal



Signals from two capacitive probes 180 degrees apart monitoring the high voltage terminal



Inert gasses as insolating gas for electrostatic accelerators

The dielectric strength of the gas/mixture

Depends mainly on its capability to reduce the density of electrons that are generated when it is subjected to an electric field. For this purpose, the gas must be electronegative to reduce the number of electrons by attachment. The gas must be able to slow down electrons to capture them efficiently at lower energies and thus avoid the generation of other electrons by impact ionization.

Sulfur hexafluoride

(SF_6) is an inorganic, colourless, odourless, non-flammable, non-toxic and an excellent electrical insulator. The high dielectric strength is a result of the gas's high electronegativity and density. Exposure to an arc chemically breaks down SF_6 though most of the decomposition products tend to quickly re-form SF_6, a process termed "self-healing”.

Dielectric field strength N_2 and CO_2 relative to SF_6

CO_2	0.32 – 0.37
N_2	0.34 – 0.43

In practice mixtures of N_2-O_2 under lightning impulse voltages exhibit better performance (dielectric strength) than those of N_2 or CO_2 on their own

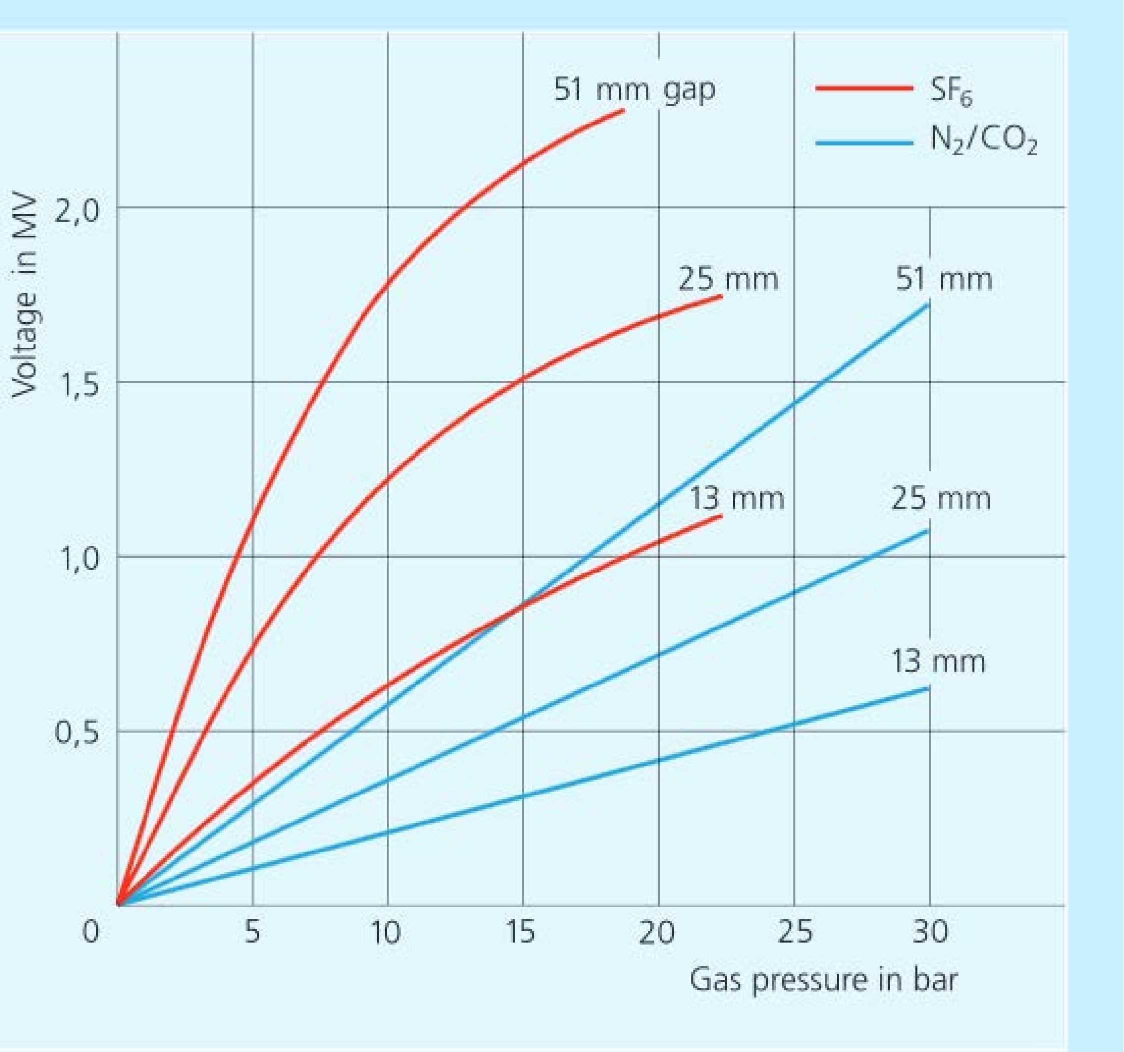
Pressure tank and inert gas

- Typical gas mixtures

SF_6	N_2	CO_2	Pressure (atm)	U_{max} (MV)
	80 %	20 %	14	9.6
60 %	40 %		6	9.7
100 %			7	13.0

- Good dielectric gas: SF_6 has withstood voltages of 40 MV/m at 8 bar
- Very important to note: gas purity and dryness
- Example: moisture in SF_6
  - o Reduction of the dielectric strength
  - o Formation of toxic gases

Relation of breakdown voltage to pressure comparison SF_6 and N_2 / CO_2-mixtures (IEEE Trans. Pow. App. Syst. 66 [1963] 357)



Toxicity of some by-products resulting from the decomposition of SF6

Gas	Toxicity	
	Tolerated Quantity (mg/m^3)	Degree of Toxicity
SF_4	0.1	Moderately toxic
SOF_4	2.5	Little toxic
SOF_2	2.5	Little toxic
SO_2F_2	5	Moderately toxic
SO_2	2	Moderately toxic
S_2F_{10}	0.025	Very toxic
SiF_4	2.5	Little toxic
HF	3	Moderately toxic

Van-de-Graaff Accelerator at HZB

Equipotential rings, internally connected by resistance chain, for uniform voltage drop over length.

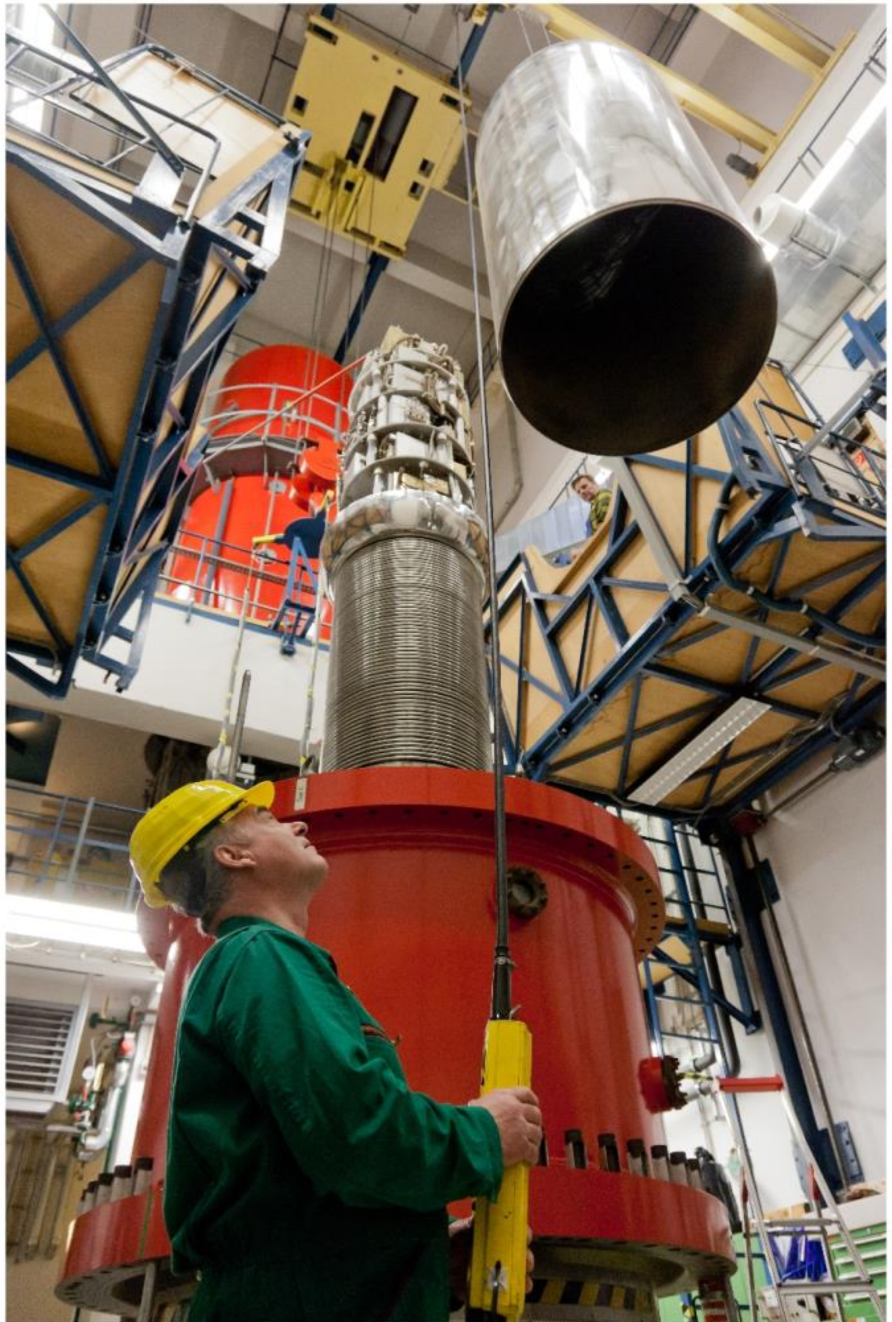
Van de Graaff accelerator at HZB

Silver: "Dome", comes over the terminal to avoid spray discharges and flashovers

Red: pressure tank, comes over the entire accelerator

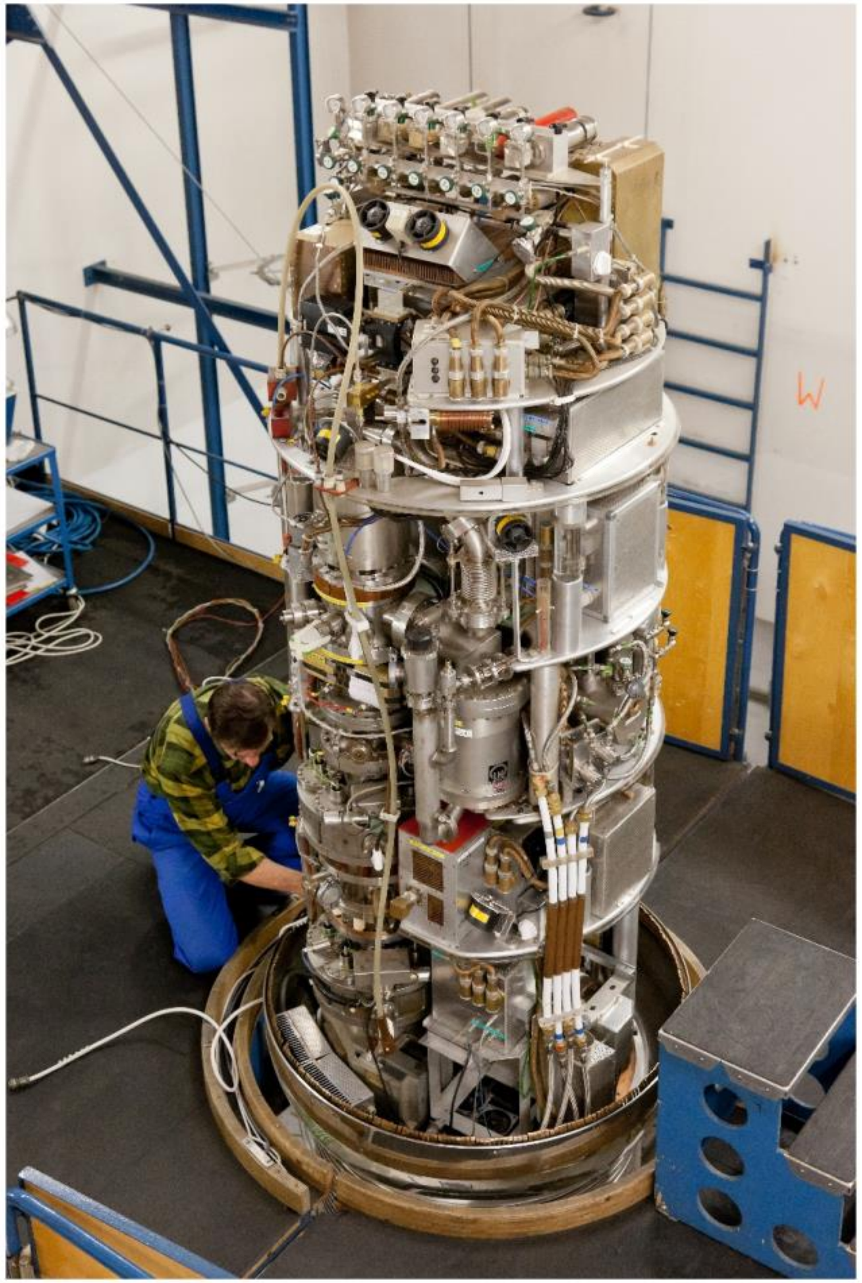
Pressure tank is pumped out and then filled with 5 bar SF_6

- Umax = 6 MV
- δV / V ≤ 10-4

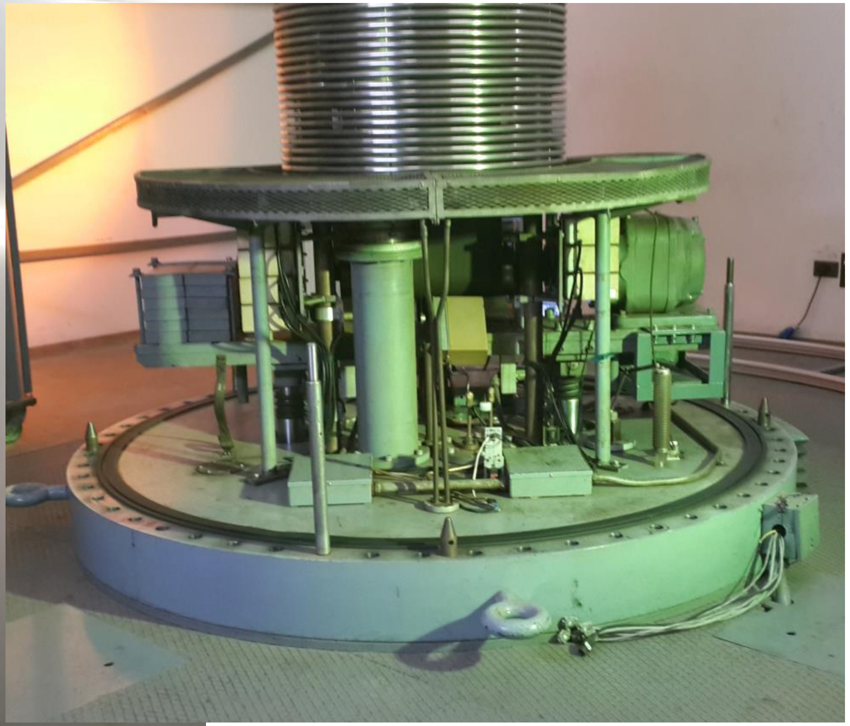


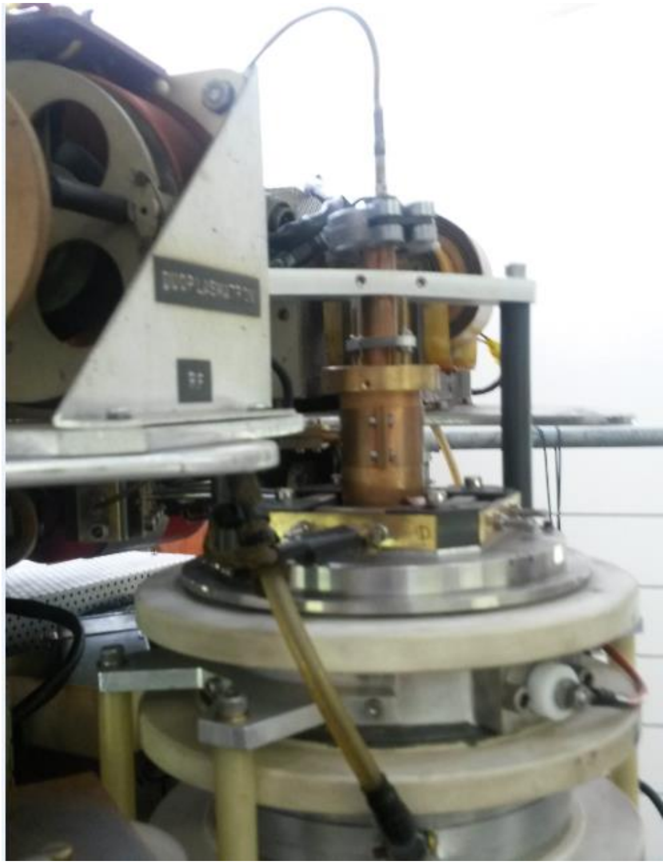
Terminal of Helmholtz Zentrum Berlin

- Terminal of the HZB Van-de-Graaff
- Permanent magnet 5 GHz ECR ion source (BECRIS)
- Gas bottles for rapid change of the ion type
- Wien filter for the preselection of the charge state
- Buncher and focusing elements



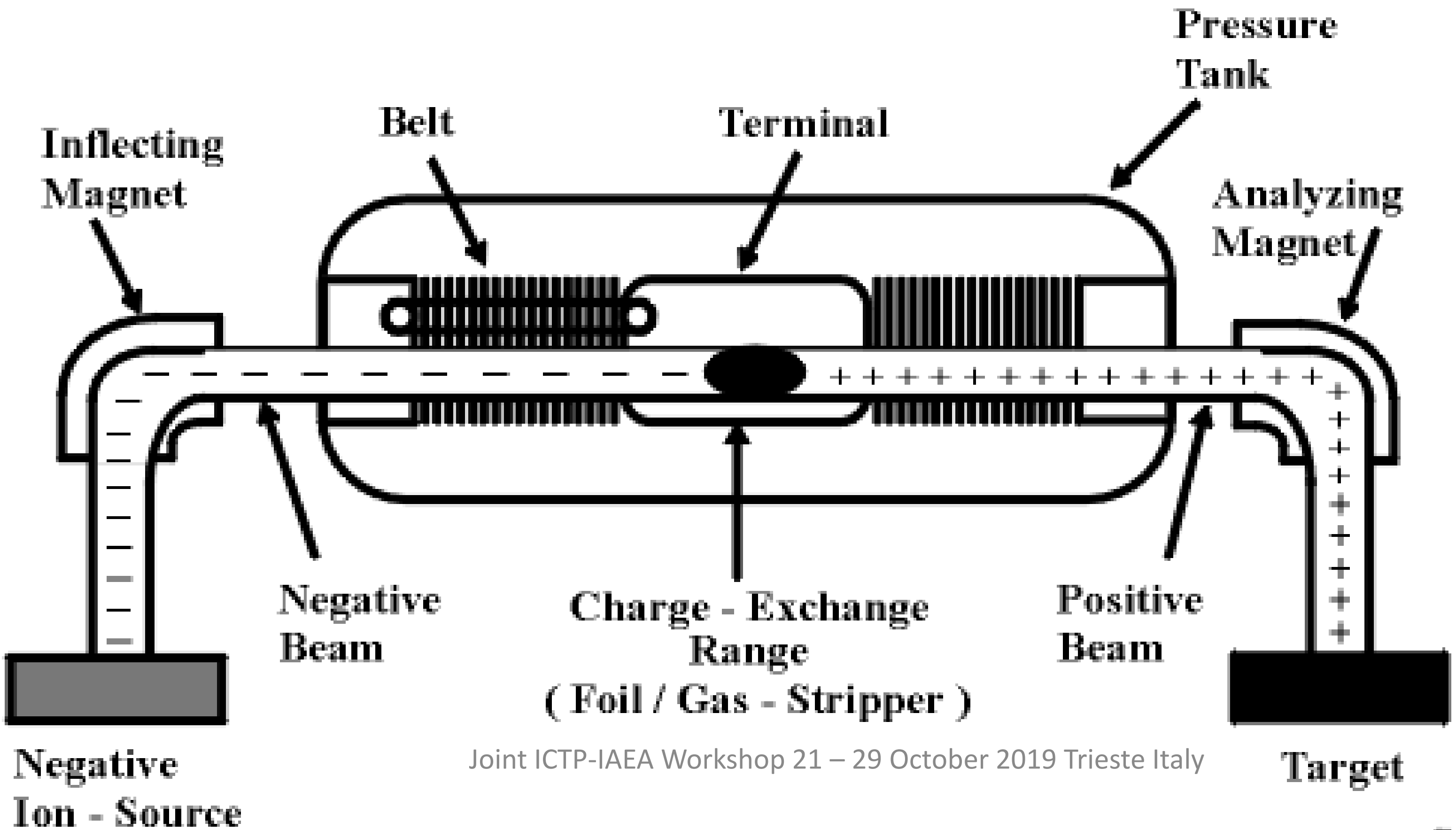
Different sections of the 6 MV CN Van de Graaff accelerator at iThemba LABS





Tandem Accelerator

- Positive voltage at the terminal (here: band generator)
- Negative ions are accelerated from source to terminal
- Charge exchange by stripping in the terminal
- Second acceleration from the terminal to ground

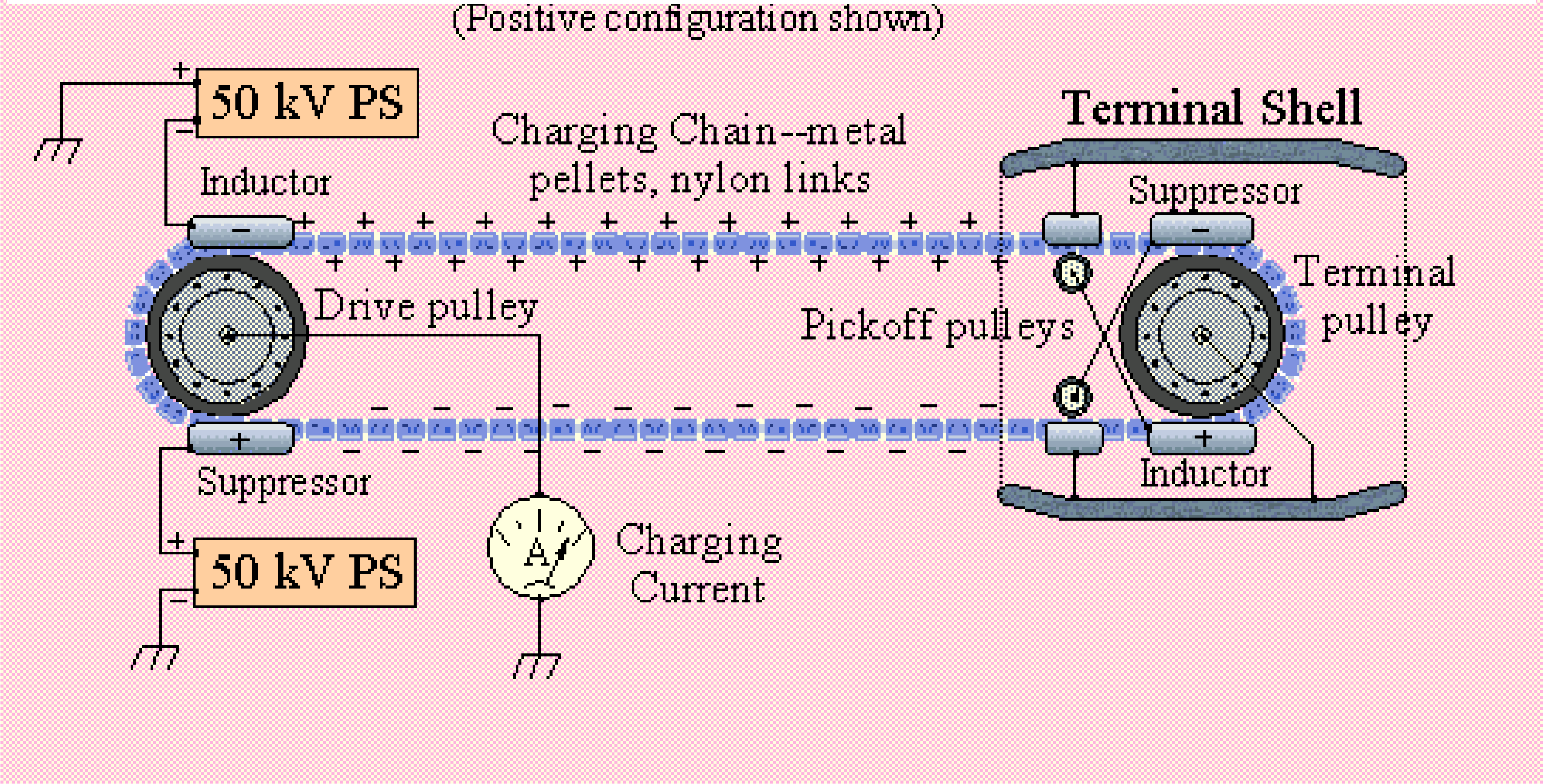


Tandem Accelerator

- High voltage generated by belt generator or by dynamitron principle (Van-de-Graaff, Tandetron)
- Require lower terminal voltage for the same energy obtained with a Van de Graaff:
- E_{kin} = eU + qU = (e+q)U
  - For 4 MeV Protons: require 2 MV terminal voltage
  - 12 MeV Cl: require 4 MV terminal voltage, for stripping in the terminal to 2+
- only for elements that also form neg. ions

  ⟶ Thus no noble gasses except He
- The ion source is at ground potential: easier access for maintenance (BIG ADVANTAGE)
- Stripping in the terminal via foils have to be reloaded:
  - higher charge states after the stripper possible
  - limited life of the foils limited, thus lower beam current longer life time of foils
- Stripping in terminal with gas:
  - Does get lower charge states than stripping with foils and also lower current
  - Can run for a number of years before the stripping gas bottle in the terminal has to be filled up

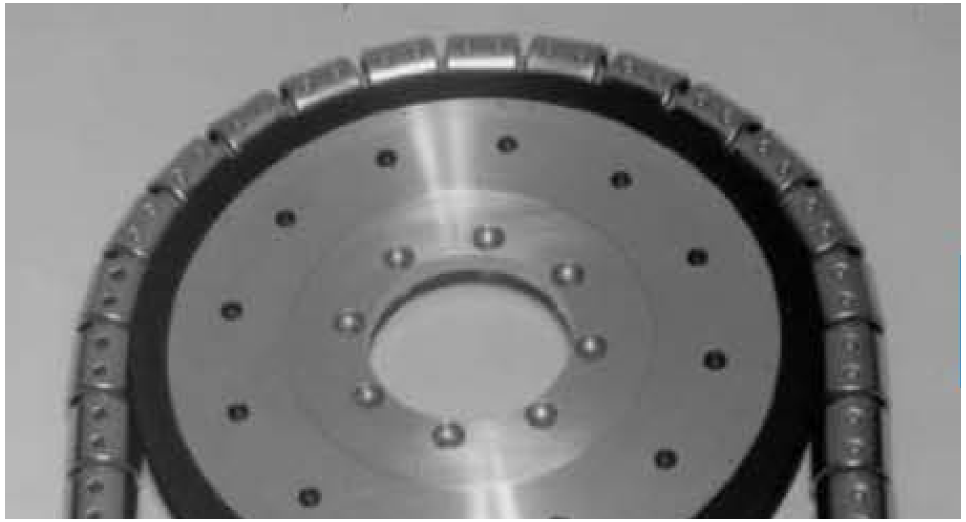
Pelletron Charging System Company NEC



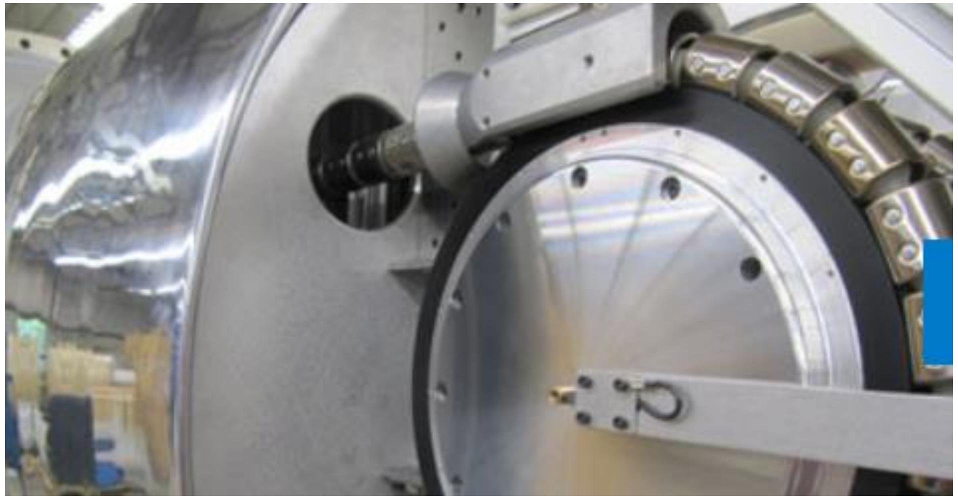
- Pelletron chain produce much less fluctuation in terminal potential because the charge is deposited on the chain of pellets by induction, a process insensitive to surface irregularities, which are a common problem with belts.
- Pelletrons run dust free and need to be replaced once every 5-7 years. Comparison with the a belt charging system it is a much cleaner environment. Pelletron chain replacement is a much faster process than changing a belt

Voltage stability with a pelletron charging system

- The high frequency ripples are due to the arrival of the individual charges on the pellets,
- The slower fluctuations are due to non-uniformities in the charging and discharging pulleys.
- The typical time-dependent voltage fluctuations on the terminal observed for a chain charging system are much less than 0.1%, and can, in a well adjusted system, approach 0.01% or better

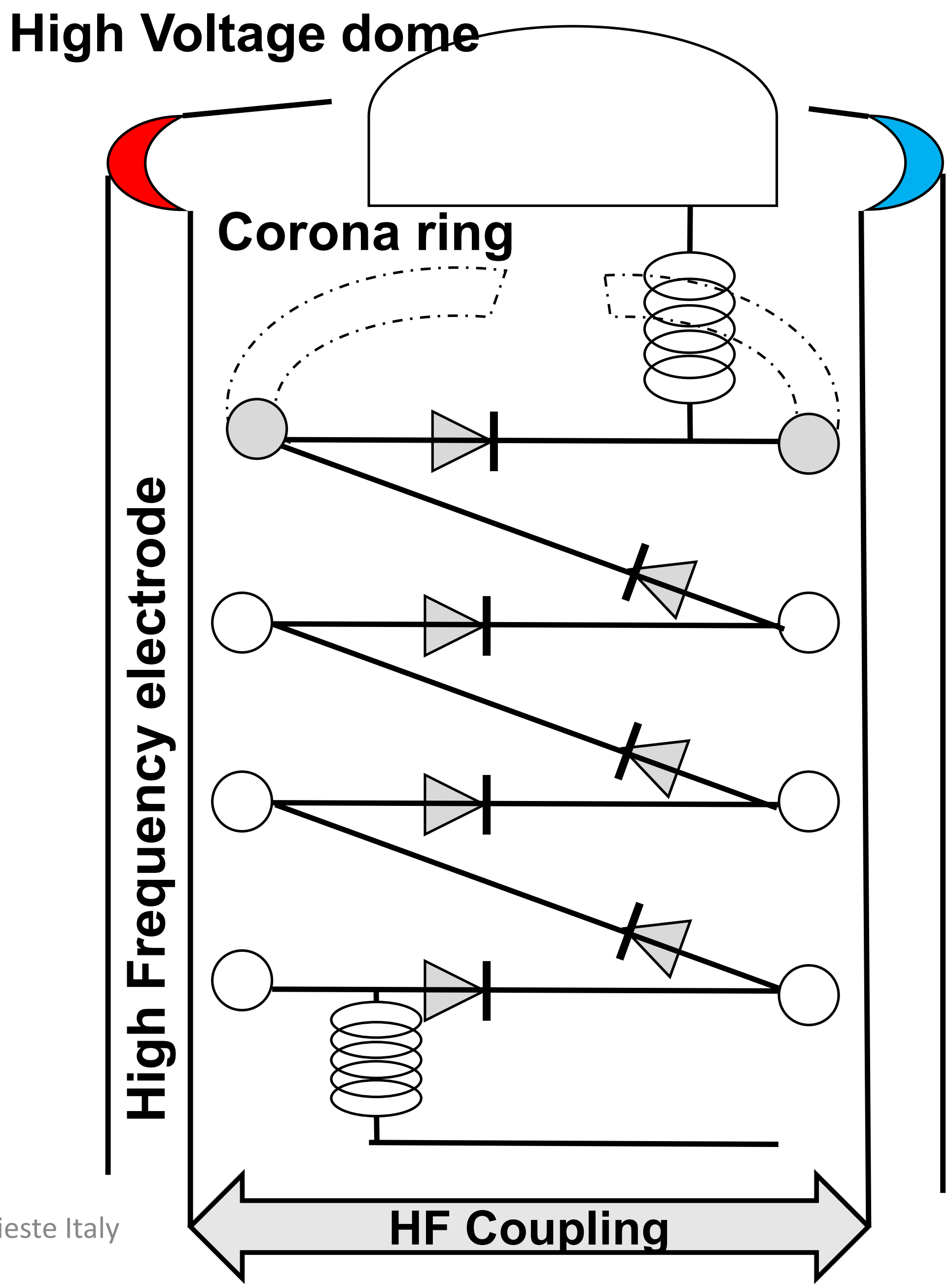


Photos from the NEC web page

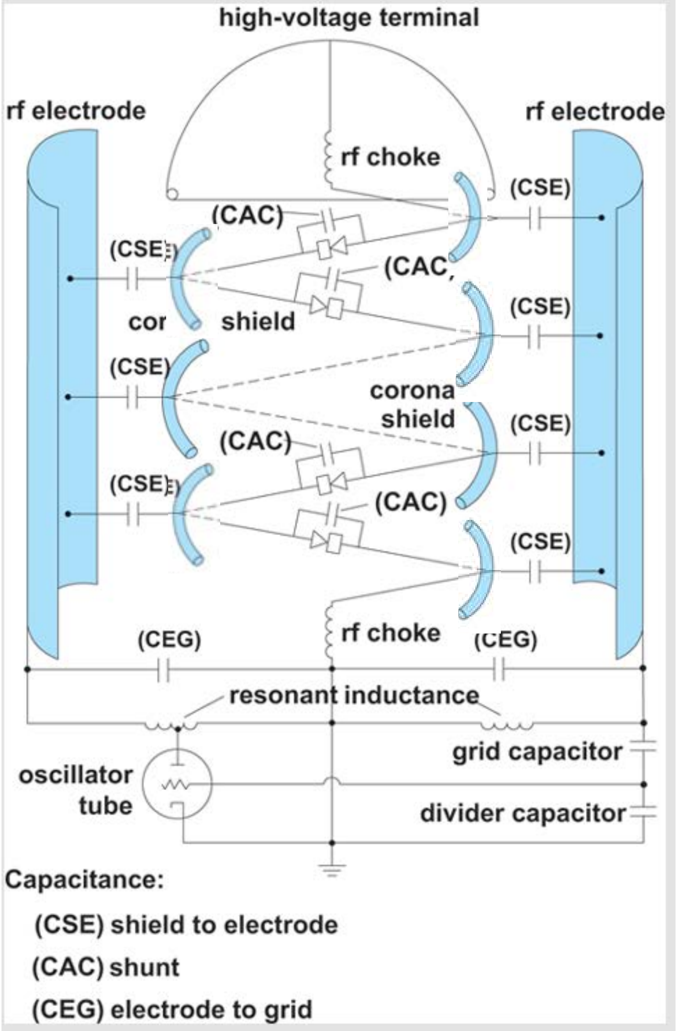


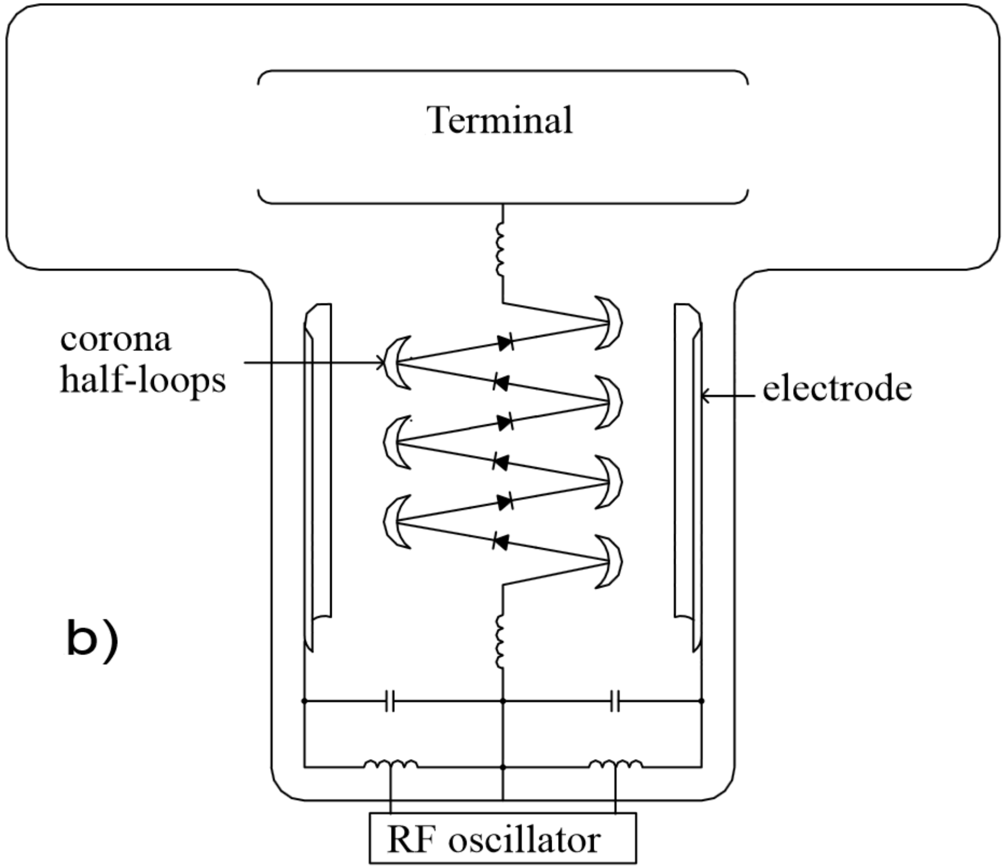
Dynamitron, Tandetron

- Further development of the cascade generator
- Semicircular RF electrodes
- Rectifier diodes connected via semicircular coronal rings
- between HF electrodes:
  strong RF field with some 100 kHz
- → Waiver of smoothing capacitors possible
- In corona rings, HF current is induced
- → Rectifier chain capacitively coupled to RF electrodes
- δV/V ≤ 10^{-3}
- 3 MV tandetron can deliver 500 micro ampere of beam current
- Manufacturer :
  - Radiation Dynamics Inc
  - HVEE



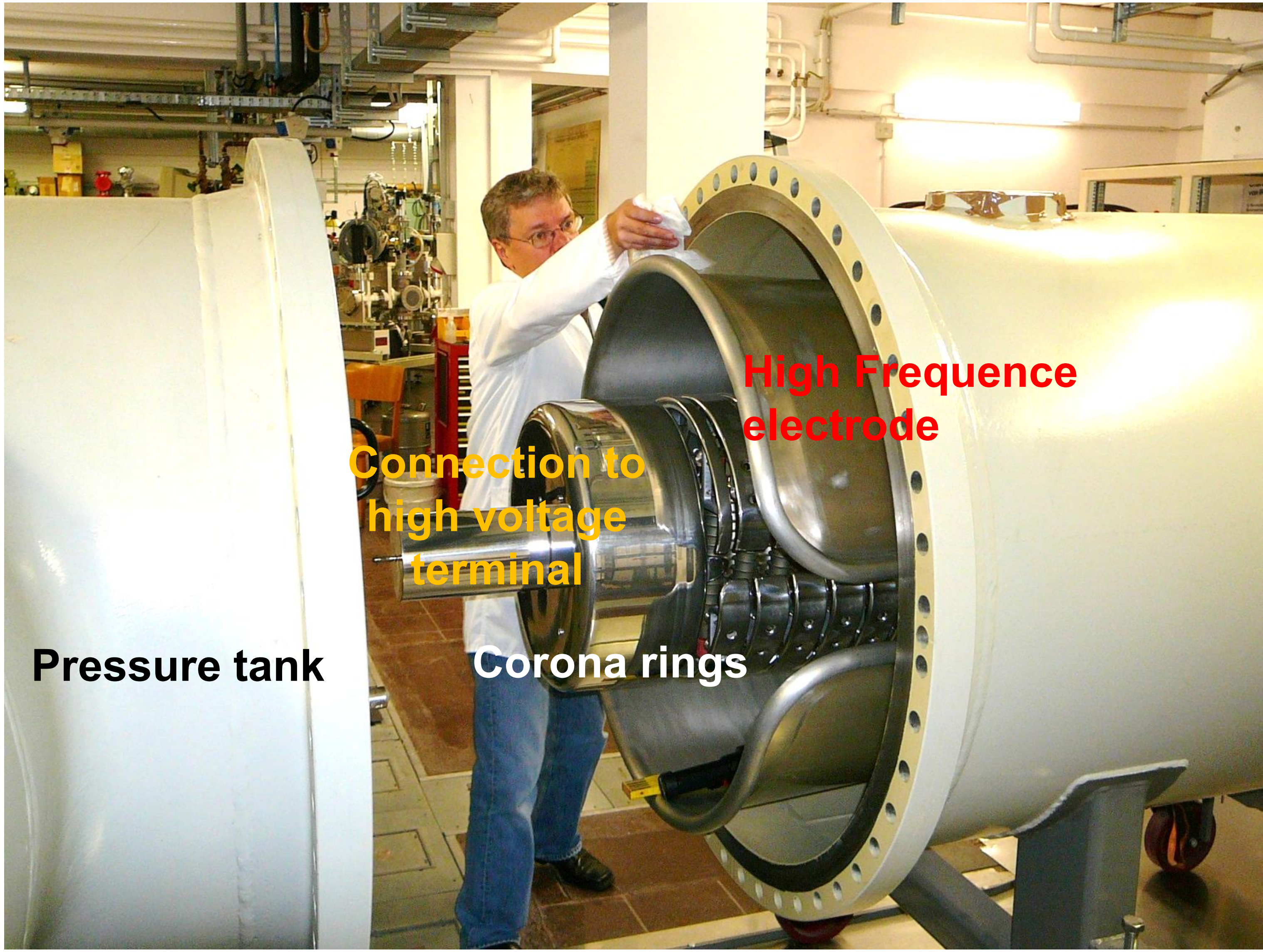
Dynamitron also known as Tandetron





Tandetron at HZB

- 2 MV Tandetron from the company HVEE
- Used from 2011 as injector for the K130 cyclotron used for eye therapy

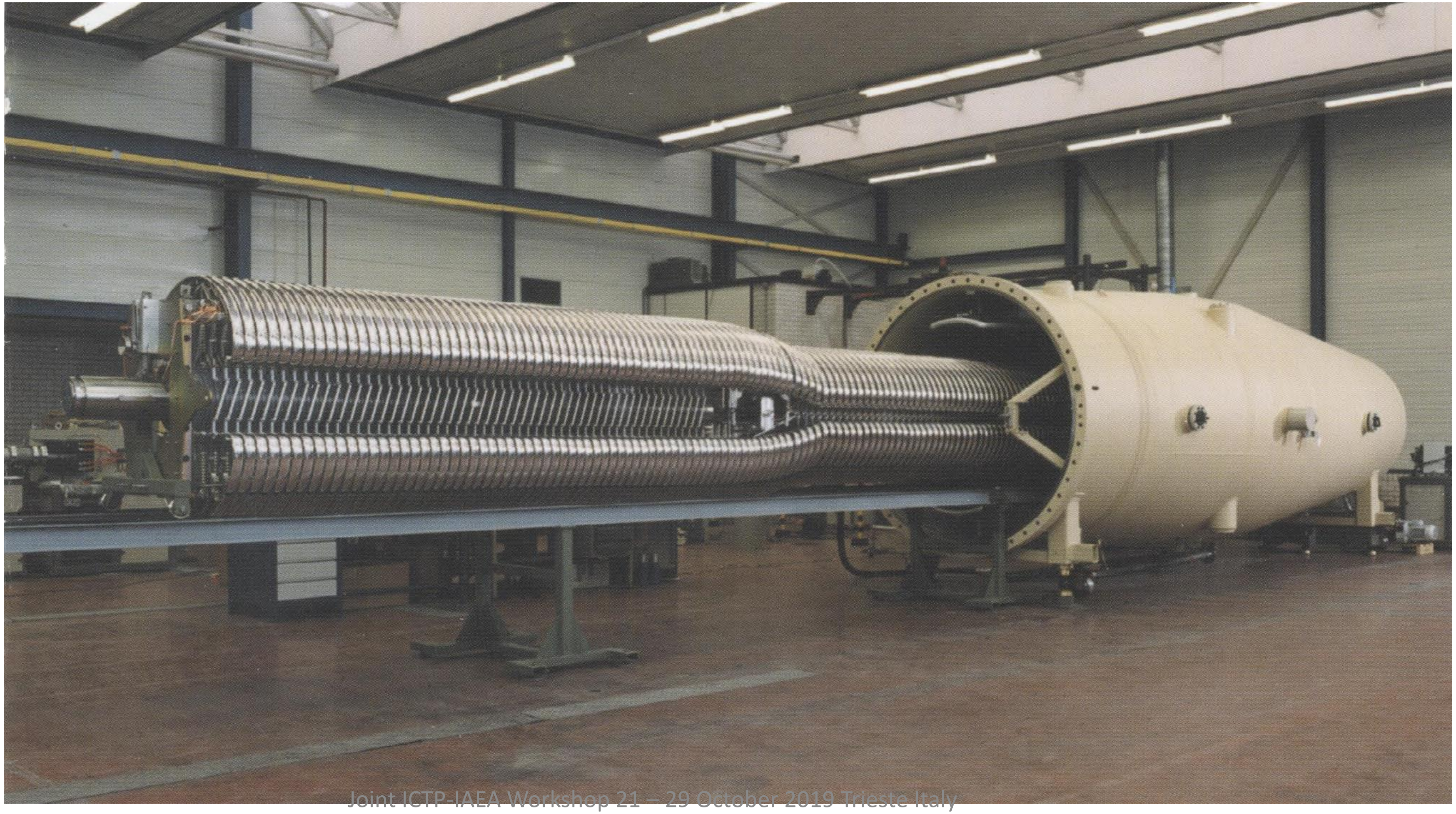


Tandetron Accelerator at HZB

- Tandetron HZB, U = 2 MV
- Voltage generation via Dynamitron principle
- 2 ion sources for improved realibility

Tandetron 6 MV accelerator from HVEE

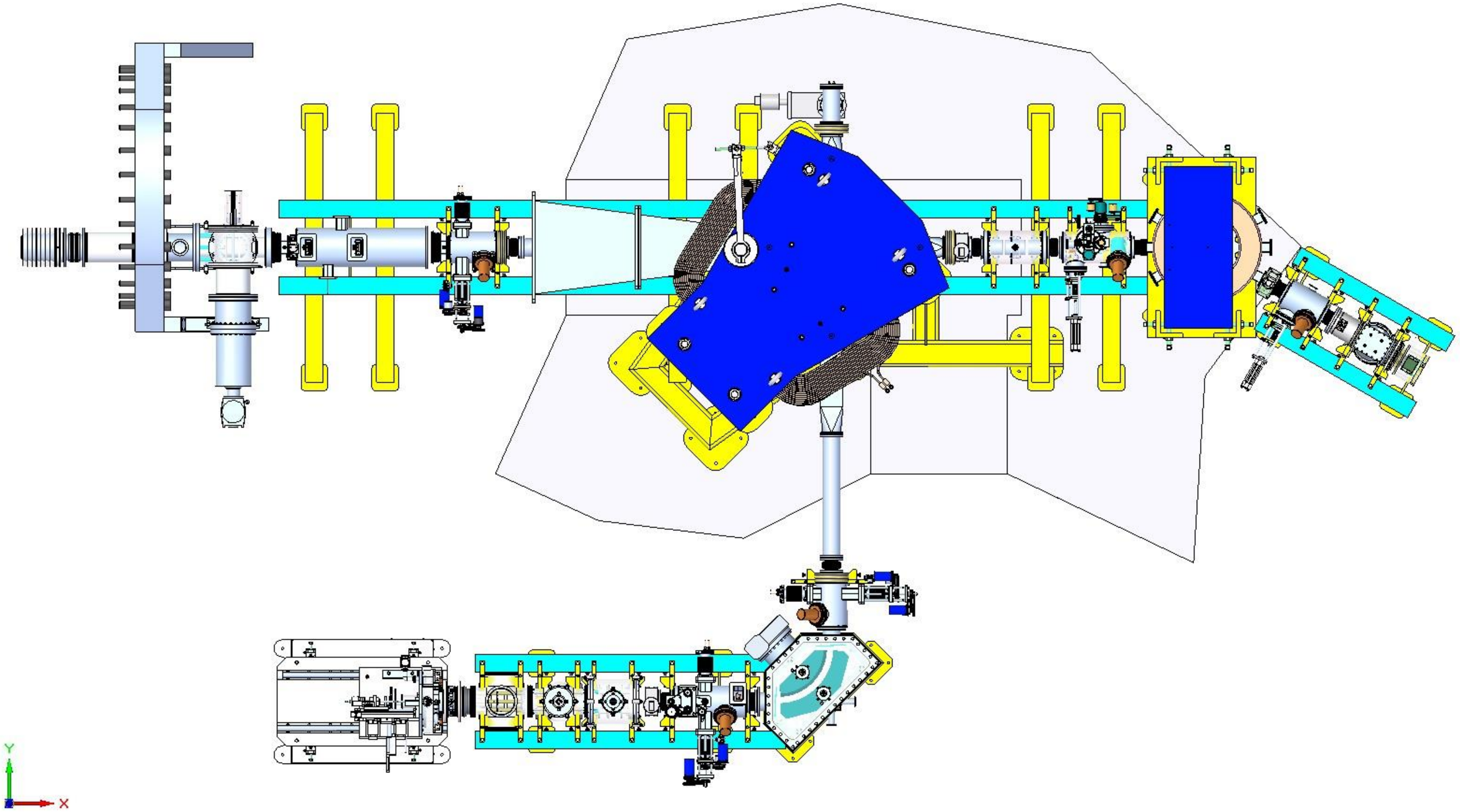
On the market 6 MV tandetron and they have a design for 8 MV tandetron



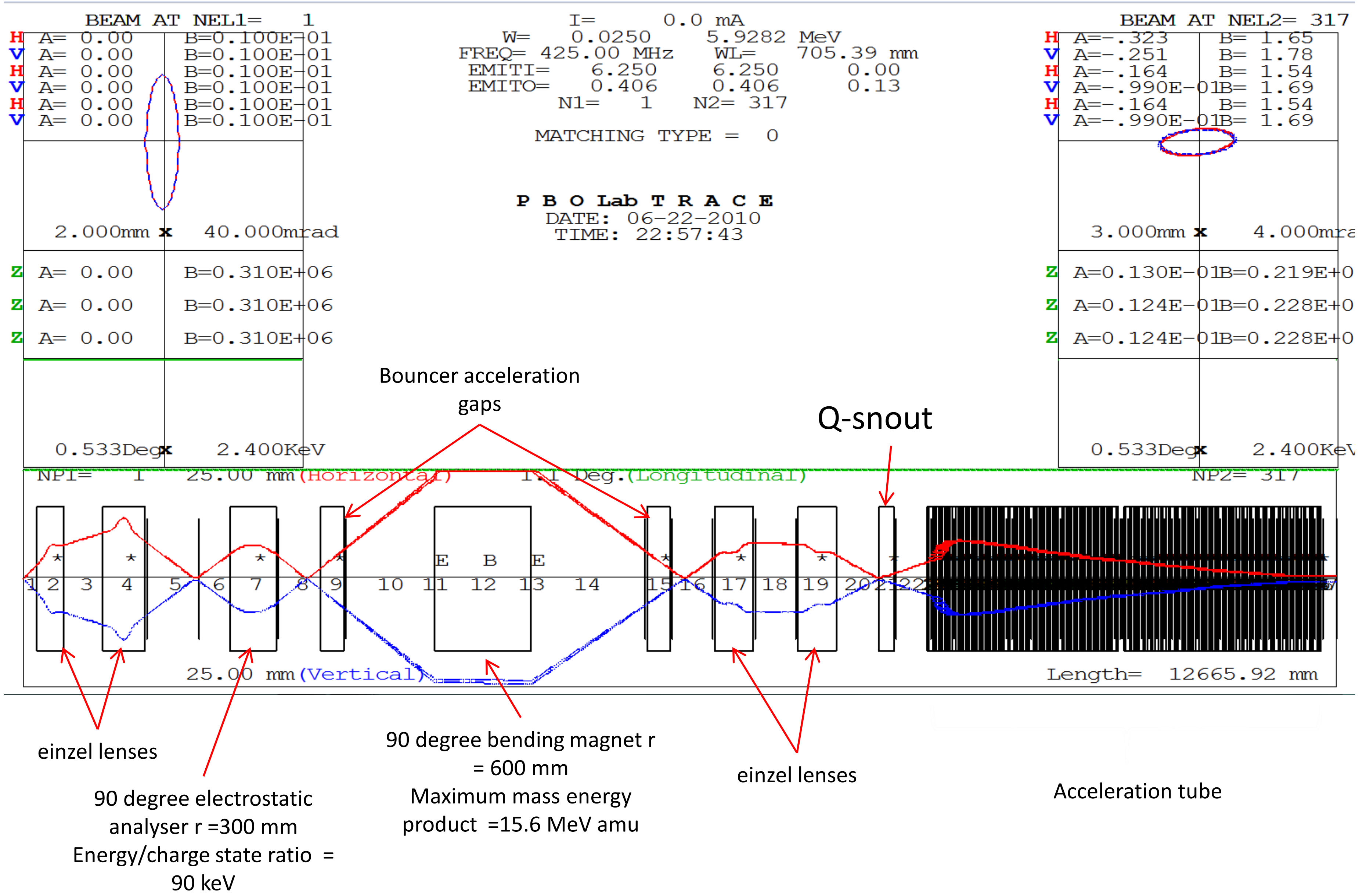
iThemba LABS 6 MV EN Tandem accelerator used for AMS

Tandem injection side

Injection system for 6 MV EN tandem accelerator of iThemba LABS

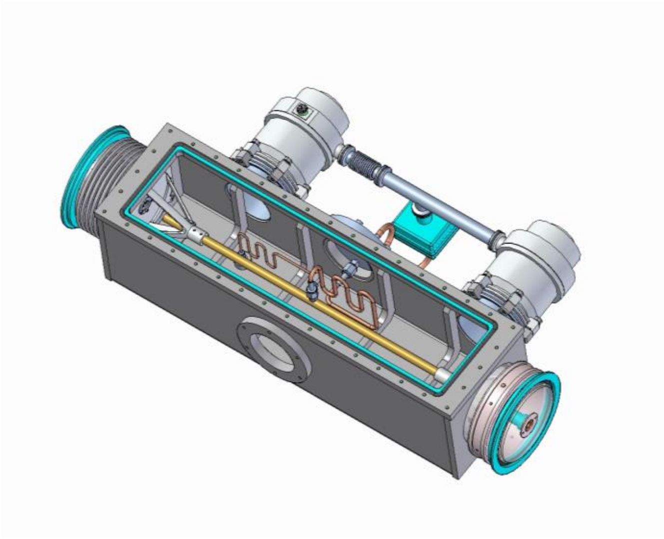


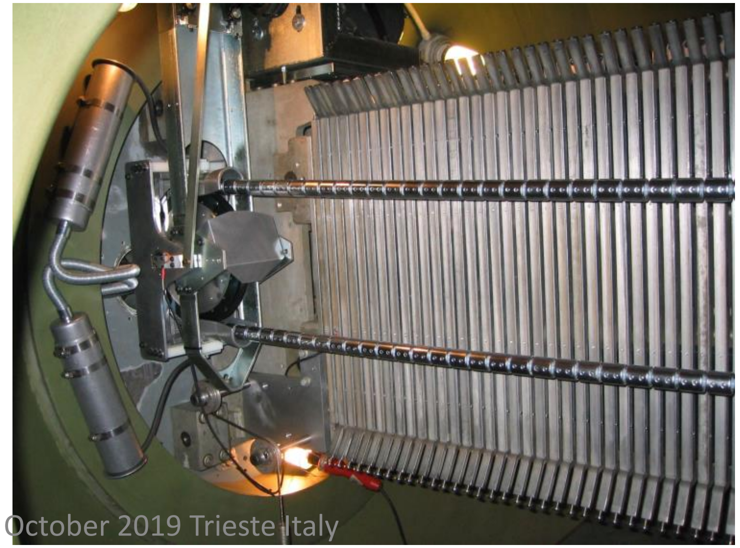
Injection beam optics from AMS ion source to middle of tandem

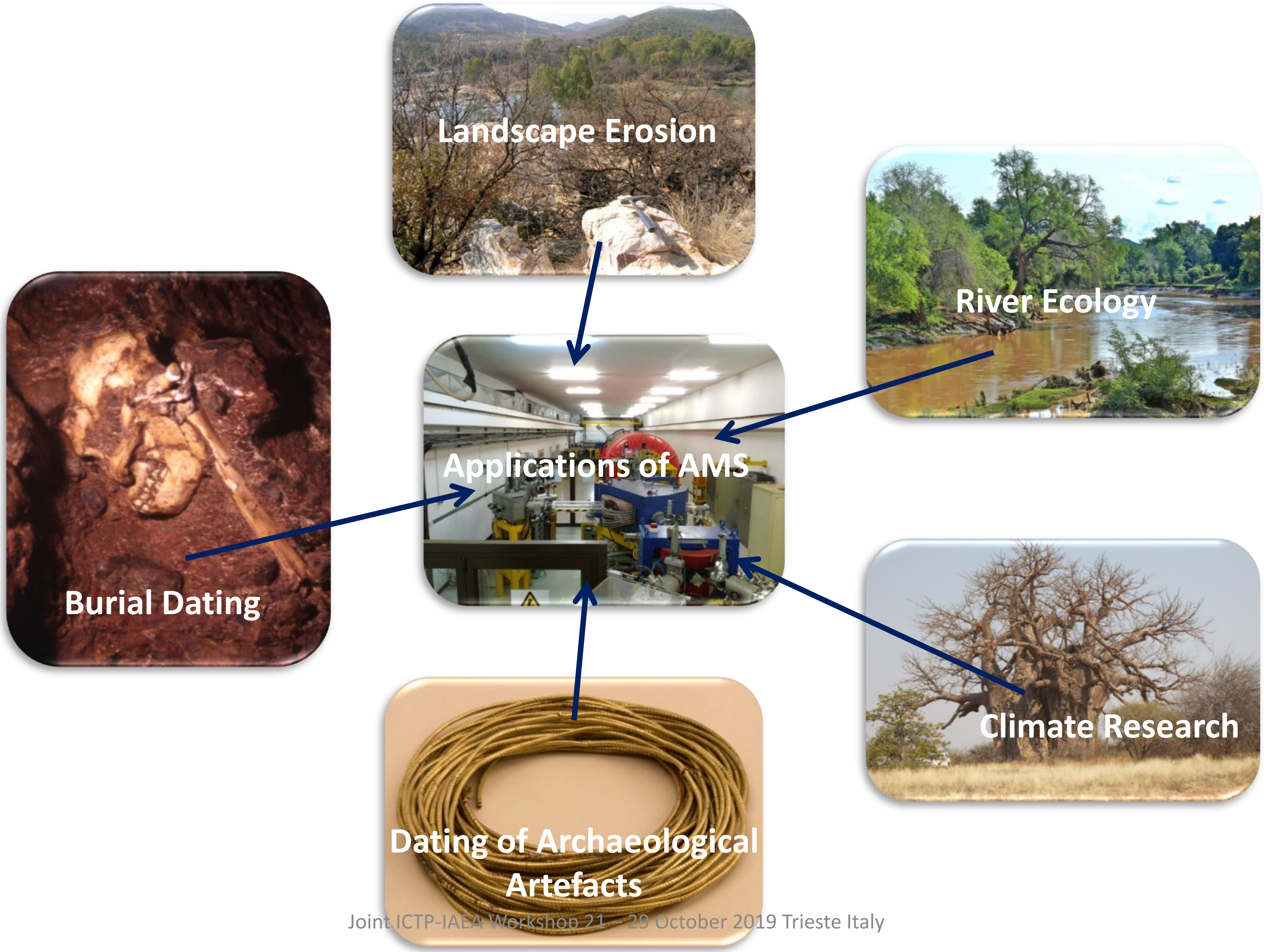


Extraction side of Tandem before the refurbishment

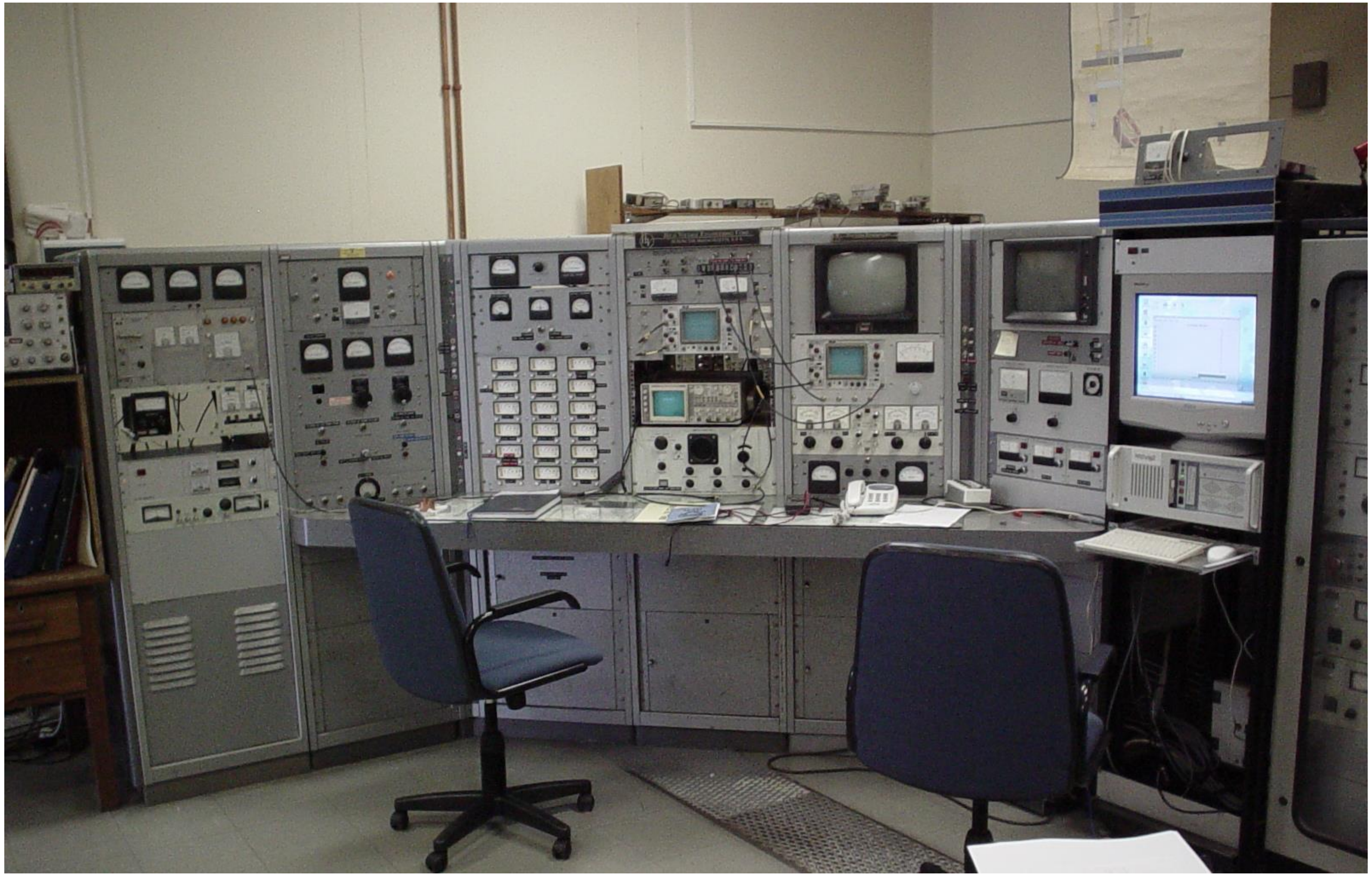
Refurbishment of the 6 MV EN Tandem Accelerator



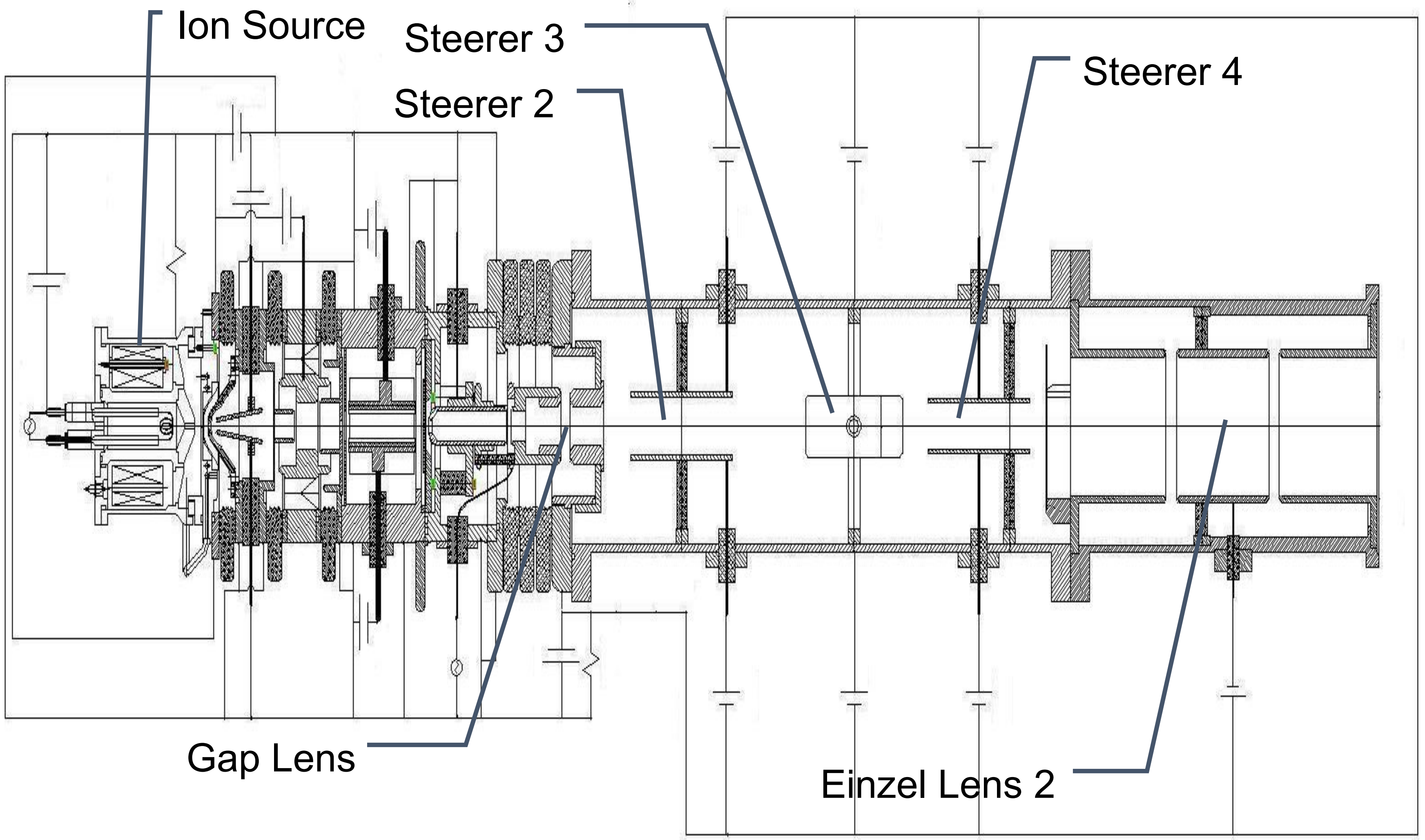



Landscape Erosion
River Ecology
Burial Dating
Applications of AMS
Climate Research
Dating of Archaeological Artefacts

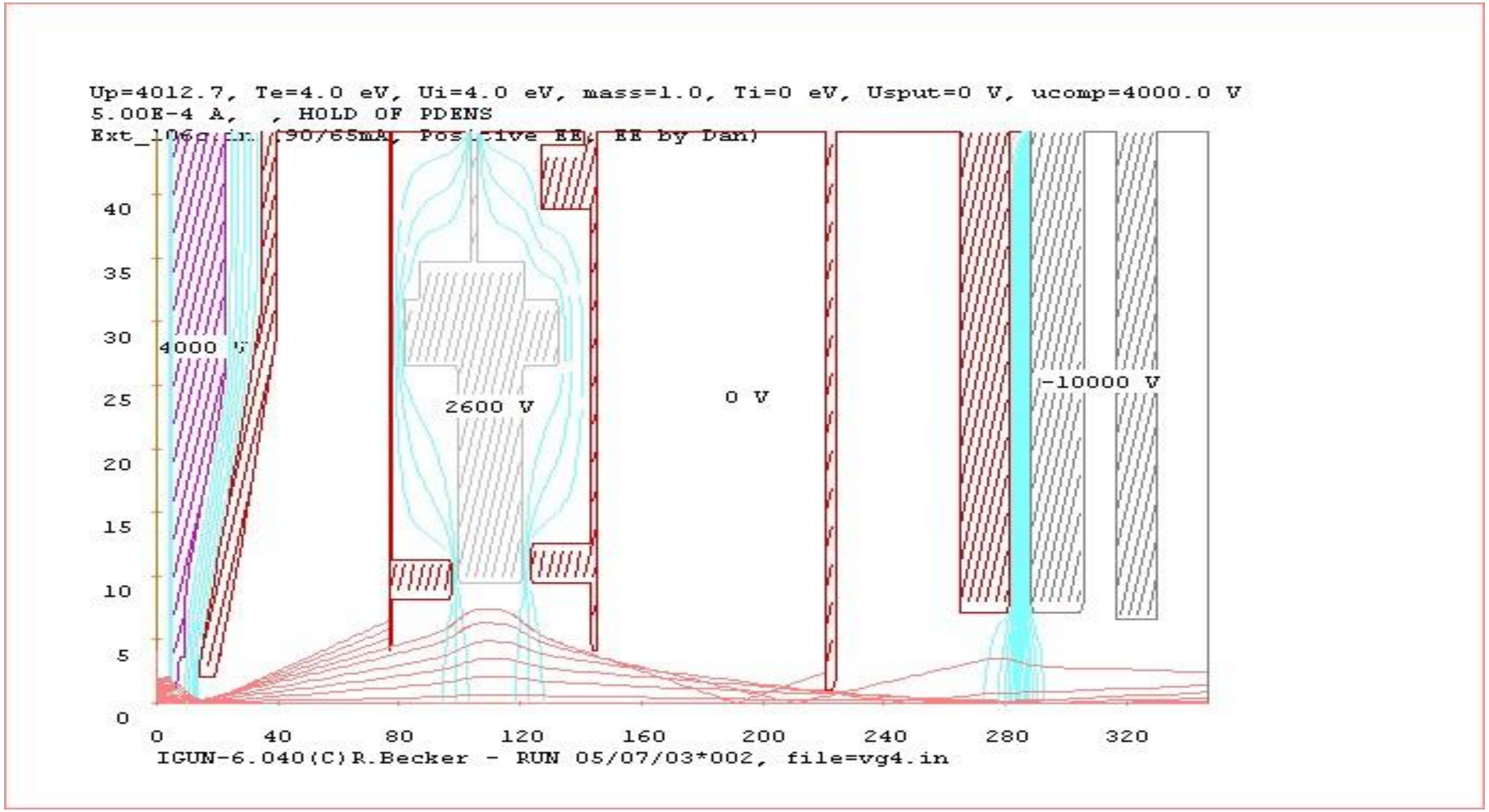
Control room 6 MV Van de Graaff 2003 iThemba LABS



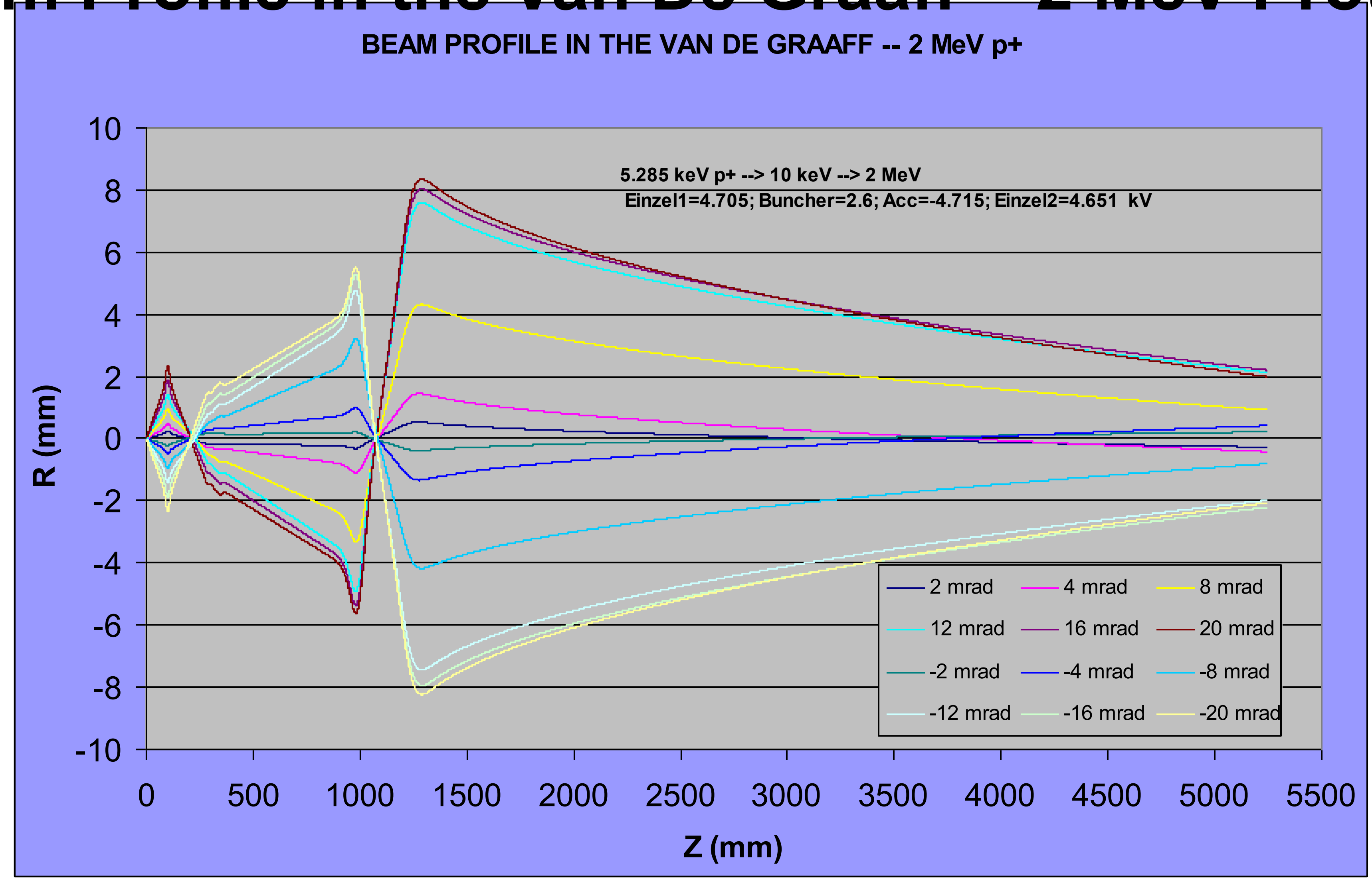
Layout – HV Terminal



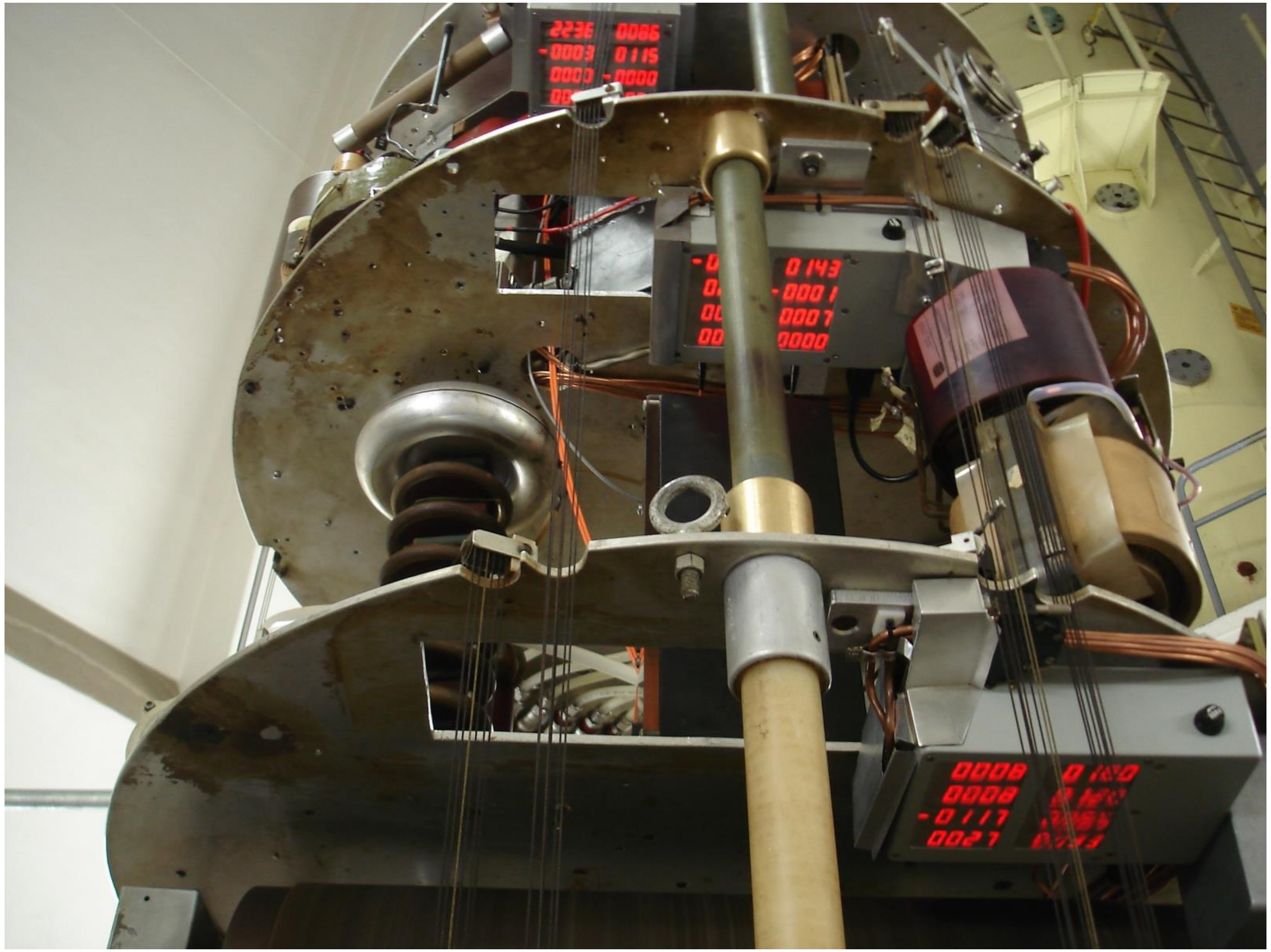
Beam Envelope in Terminal Calculated with the Program IGUN



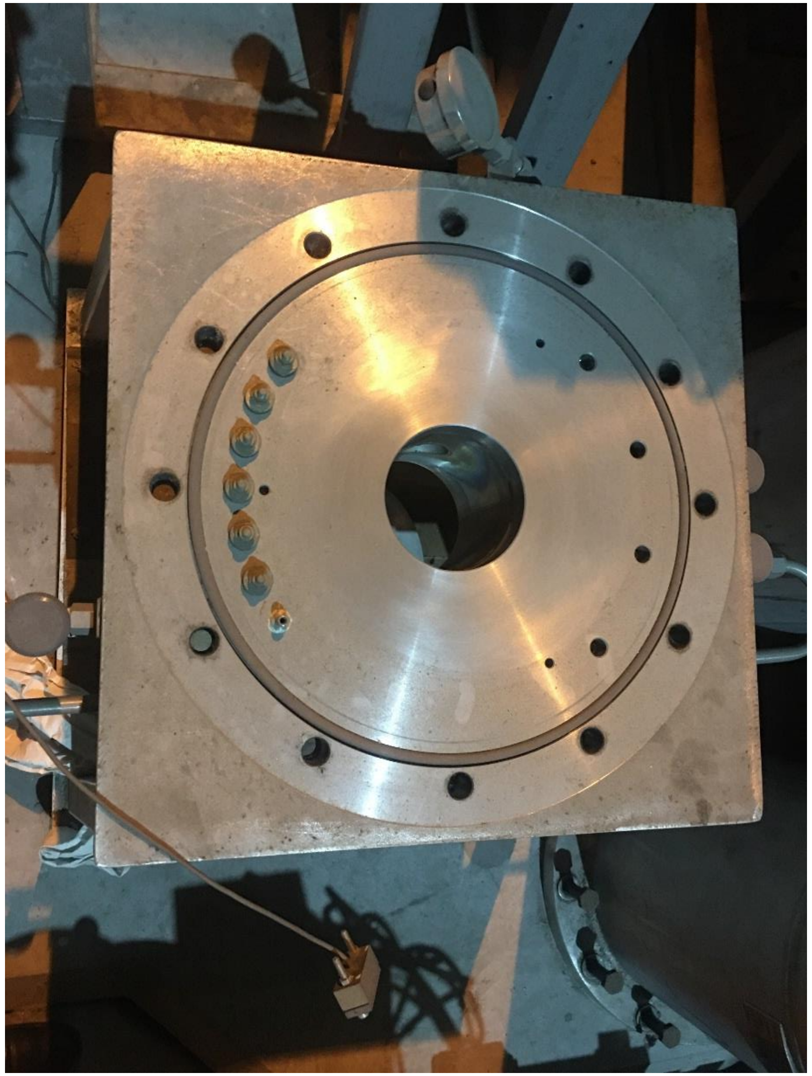
Beam Profile in the Van De Graaff - 2 MeV Protons



24 Digital meters installed in the terminal of the 6 MV CN Van De Graaff (survive 16 bar pressure and all the sparks for 6 Years)



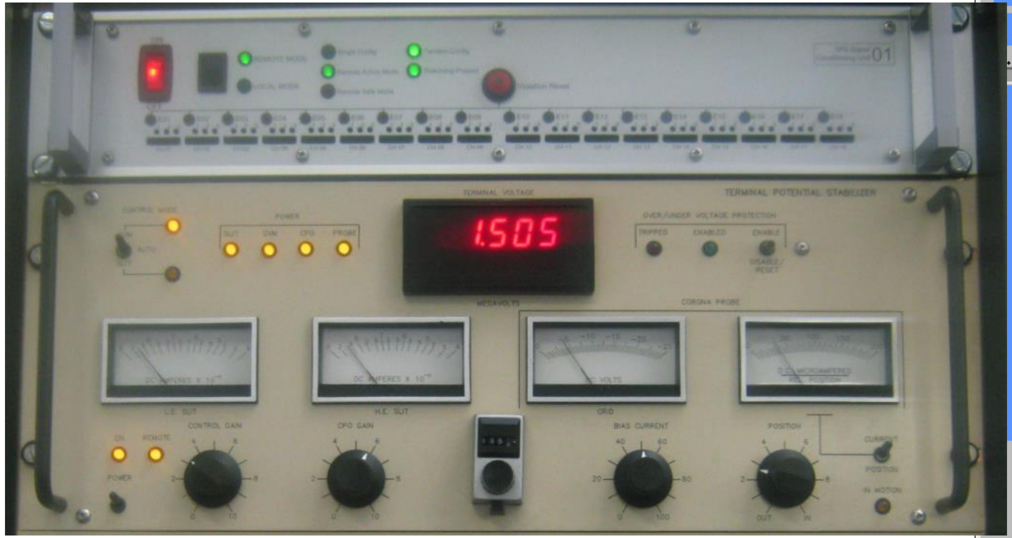
Pressure vessel for pressure testing components in the high voltage terminal

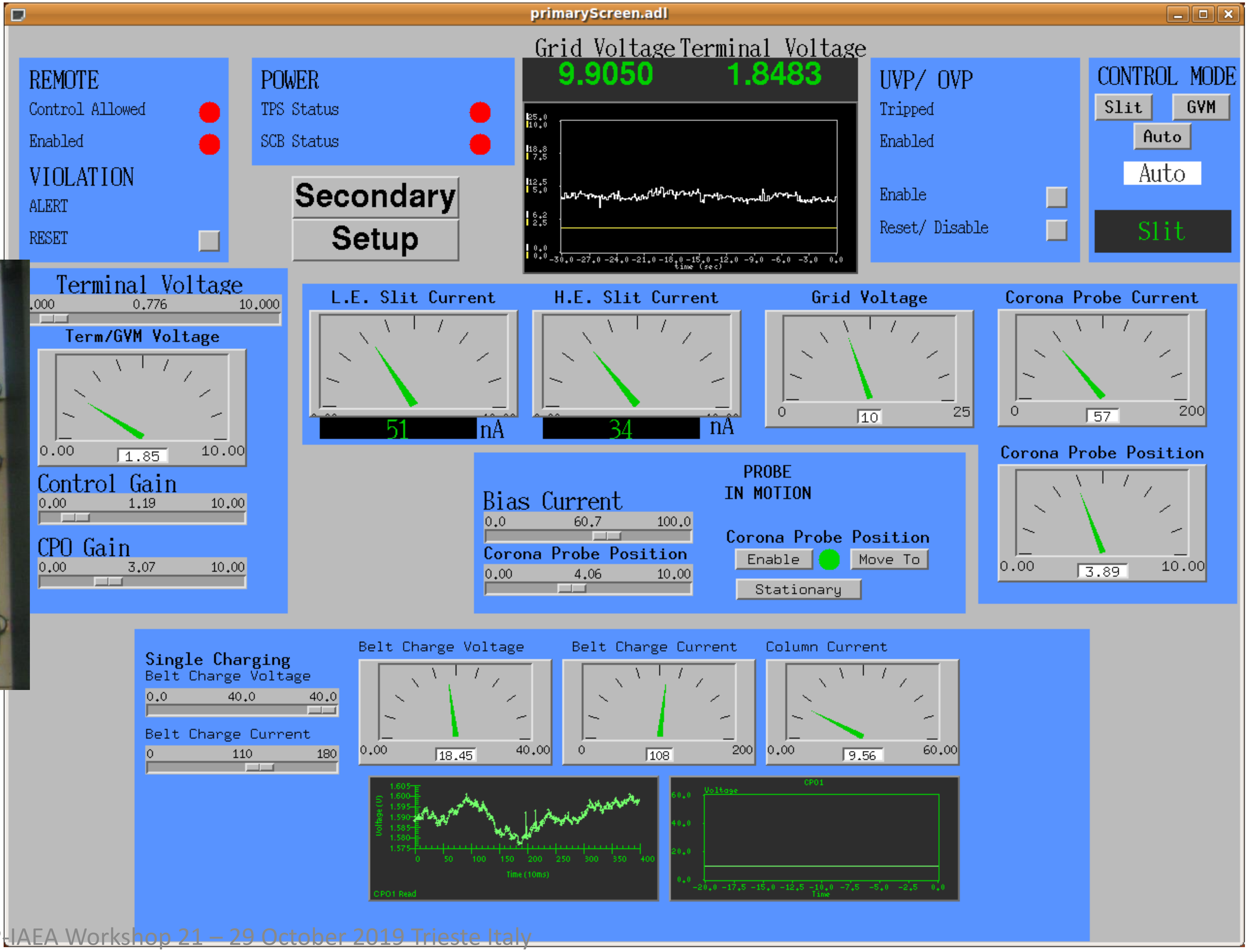


Larger pressure vessel to pressure test the complete assembled high voltage terminal of the Van de Graaff accelerator

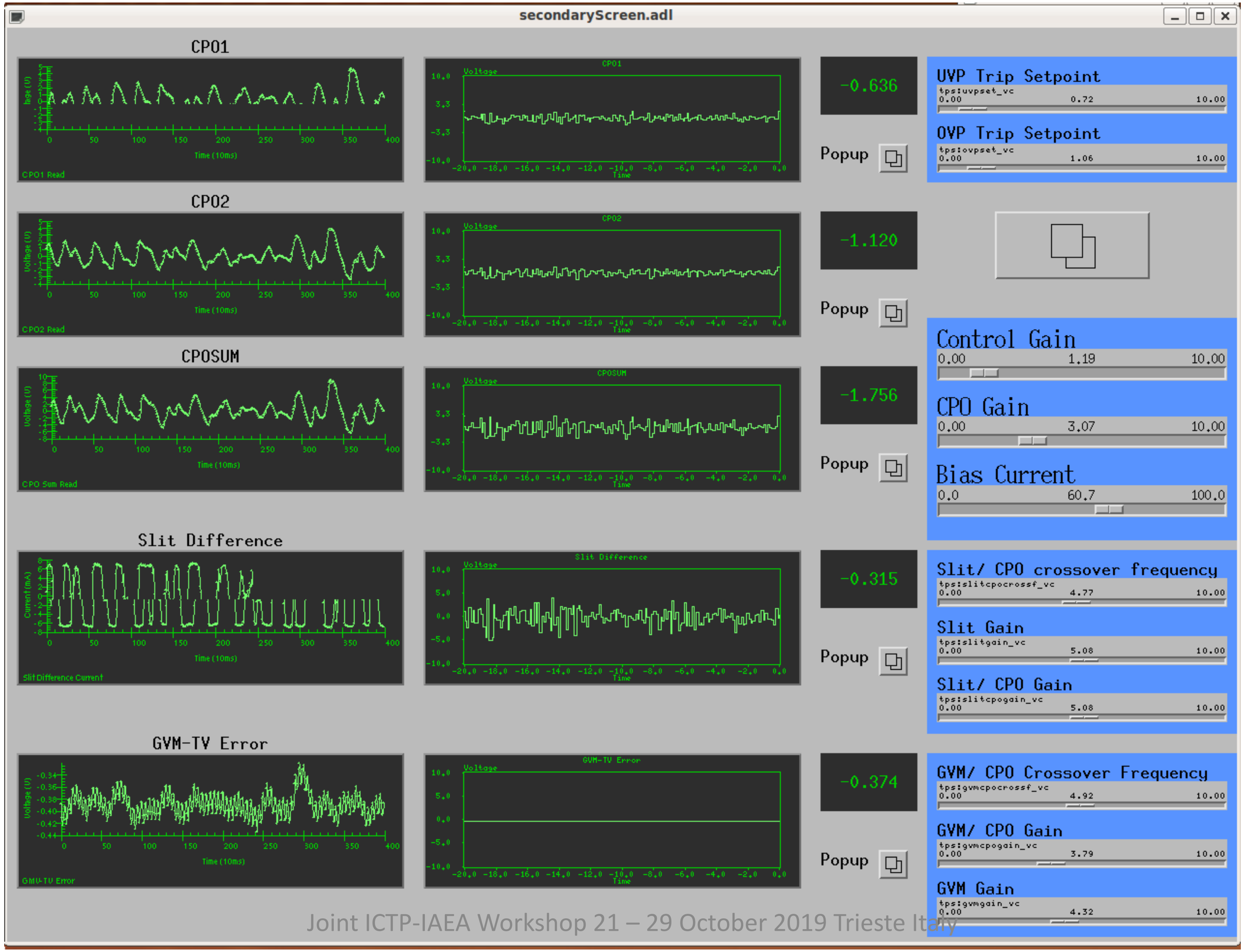
Van de Graaff terminal voltage stabilizing unit

Voltage stabilization by controlling the corona current

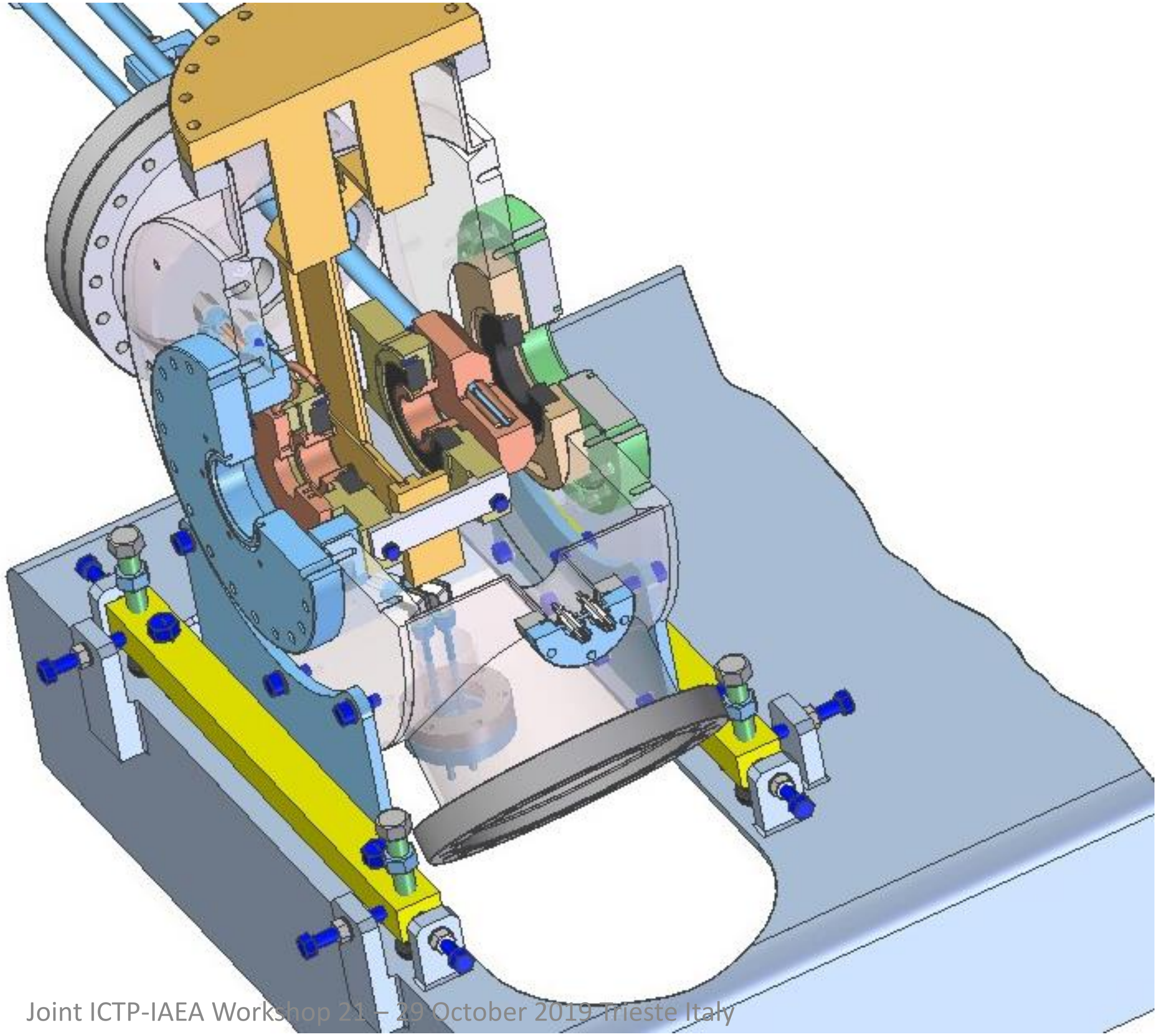




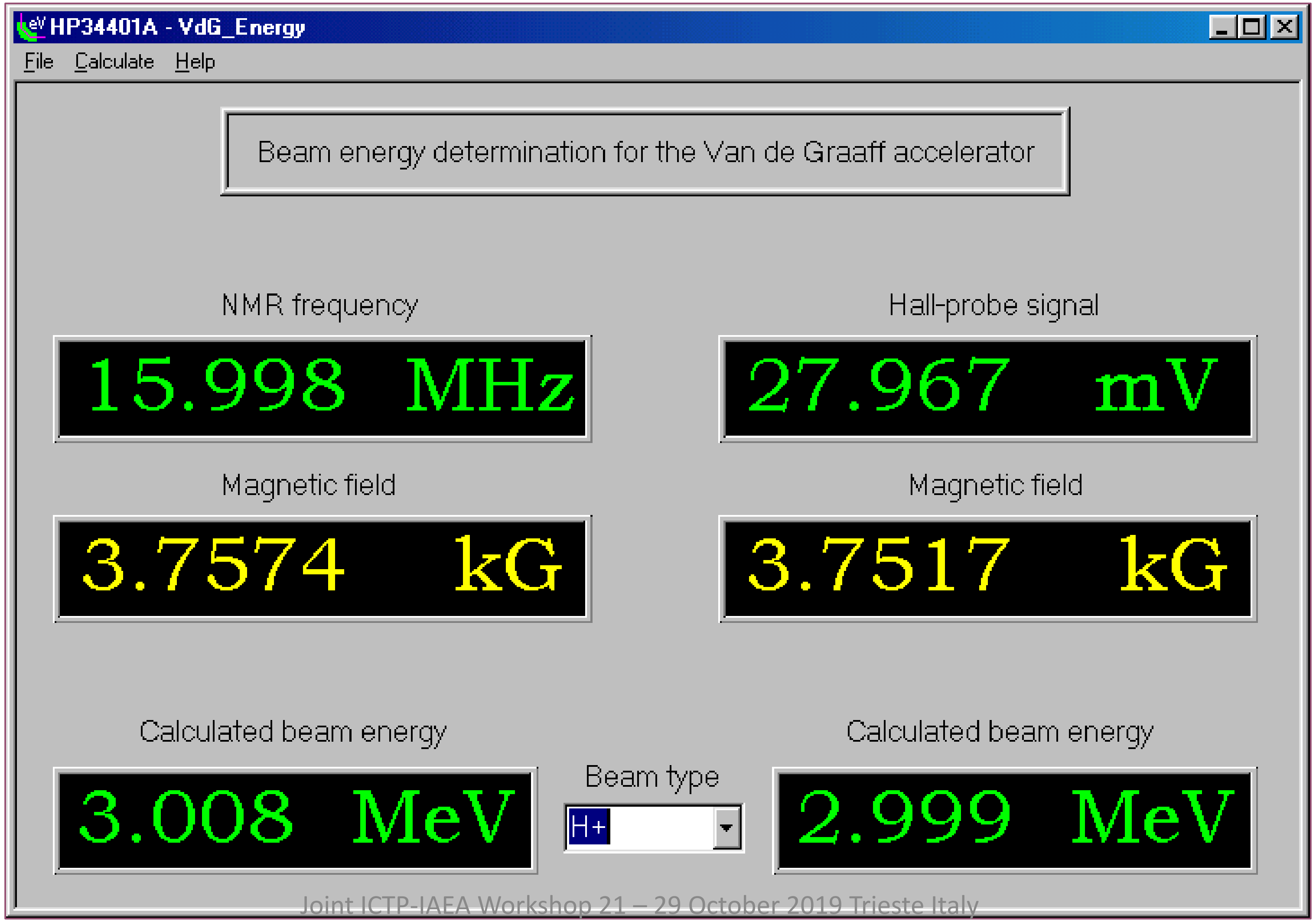
Displaying information of the 2 capacity pickups, generating volt meter and current difference on the analysing slit jaws



New energy stabilization slits system



Energy measurement at the Van de Graaff



Control Room 6MV CN Van de Graaff 2014
iThemba LABS

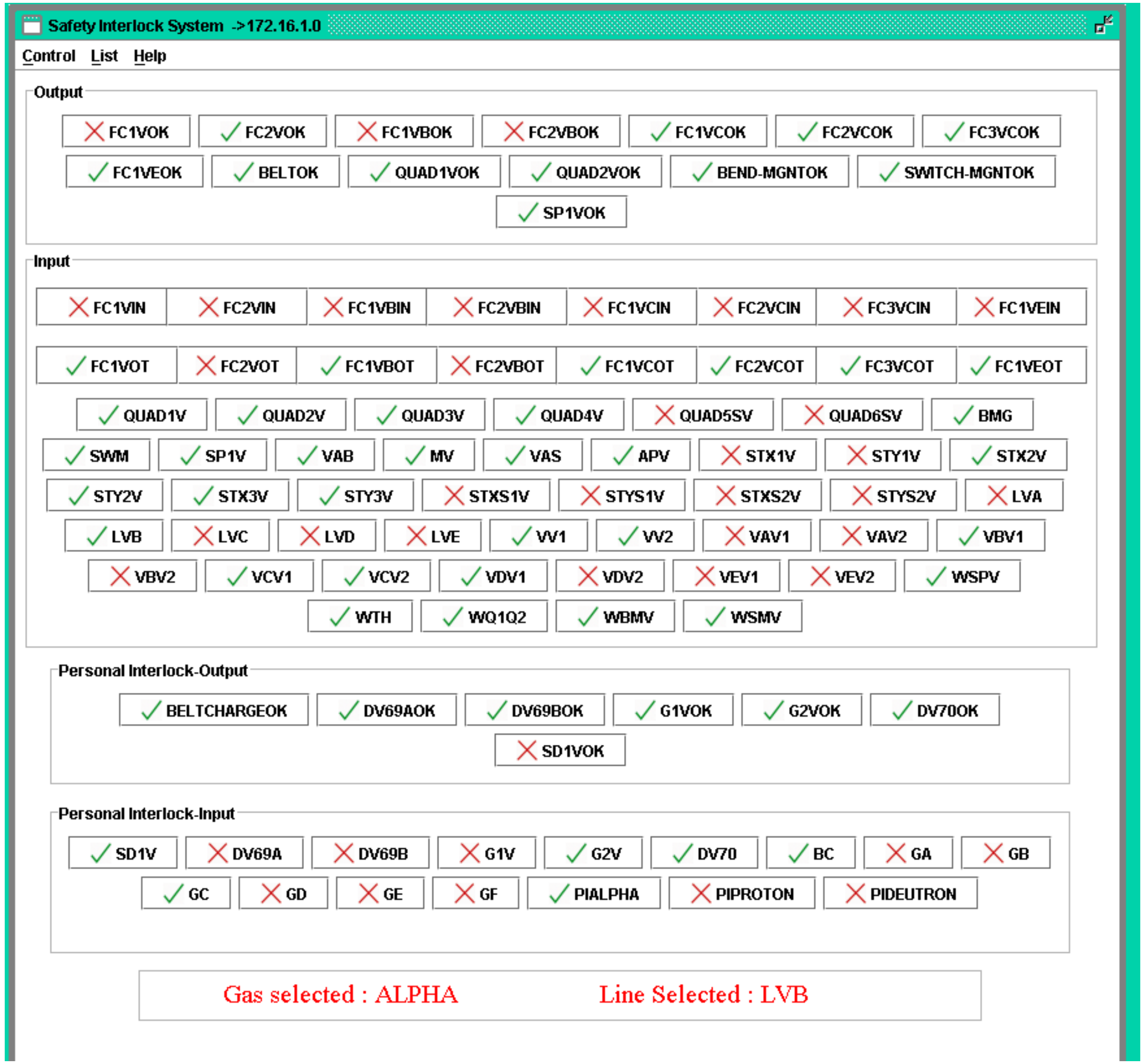
3 MV Tandetron at iThemba LABS

High energy beam line of the tandetron accelerator

What to take into account to ensure a well maintained accelerator facility

- What is the maintenance strategy of your installation? (predictive, corrective, emergency, regulatory maintenance)
- How to explain to the management that the consolidated cost of equipment including maintenance cost and running cost should be considered when designing and purchasing new equipment?
- Using in-house resources or an external company to do the maintenance
- How to ensure equipment is easy to maintain? needing little time to be fixed, replaced, etc.?
- How to handle large system maintenance as in the case of a cooling plant refurbishment when the facility is aging?
- Maintenance of software (controls, equipment firmware, etc)
- Maintenance impact on the planning of the shutdown periods (what strategy?)
- Maintenance strategy and prioritization the resources in a large accelerator complex

Safety interlock system for personnel and equipment safety



Parts list of Van de Graaff accelerator

Van de Graaff Parts List

Terminal

Item	Image	Part No:	Company	URL	Dimensions	In use	Spares	Price
Duoplasmatron source		350	Iomex		152mm Dia 192	1	1	
Gauze Filament 80 mesh .003		G350A0302	High Voltage Engineering	http://www.highvolteng.com/				R4032
0.25uF Mica Capacitor 25KVDC		MD2BY254K	SorApower Inc	http://www.sorapower.com/		2	8	$598.00
Einzel 2 power supply						1		
Variac M2 Single phase 120V 400Hz 2.4A		M2	Technipower	http://www.inotek.com/catalog/technipower1pc.html		5	2	$248.00
Variac M5 Single phase 120V 400Hz 6A		M5	Technipower	http://www.inotek.com/catalog/technipower1pc.html		2	1	$286.00
Gas bottles						5		
High Voltage Resistor 100Meg 2%		100.4-100M-GT-A	Nicrom Electronics	http://www.nicrom-electronic.com/			100	R50
Dome						1		
3W 20KV 100Meg 1% resistor		588-MOX-2N 131006FE	Mouser	http://za.mouser.com/		25		$11.20
General purpose relay		HFW5A1201S501	TE Connectivity	www.te.com		2		$138.23
40M Resisiter		WHVL2PY-40MFB	Mouser	http://za.mouser.com/		50		$29.55
50K Resistor		WHVL2PY-50KFB	Mouser	http://za.mouser.com/		25		$29.55
Thermo electric leak			Potentials Inc	http://www.potentialsinc.com/		5		$831.60
Current Injection Transformer		220V/230V to 0.5V @ 75A	Eloff Transformers	http://www.elofftransformers.co.za/		5	1	R552.90

https://elog.psi.ch/elog/

The ELOG Home Page

Site map : [Home] [User's Guide] [Administrator's Guide] [FAQ] [Forum] [Wishlist] [Contributions] [DEMO] [Download]

* this section : [What is ELOG ?] [Screen shots] [Use cases] [License] [Talks] [Links] *

Home of the *Electronic Logbook* package by Stefan Ritt

Current version is : 3.1.2

What is ELOG ?

ELOG is part of a family of applications known as *weblogs* . Their general purpose is :

1. to make it easy for people to put information online in a chronological fashion, in the form of short, time-stamped text messages ("entries") with optional HTML markup for presentation, and optional file attachments (images, archives, etc.)
2. to make it easy for other people to access this information through a Web interface, browse entries, search, download files, and optionally add, update, delete or comment on entries.

ELOG is a remarkable implementation of a *weblog* in at least two respects :

- its simplicity of use : you don't need to be a seasoned server operator and/or an experimented database administrator to run **ELOG** ; one executable file (under Unix or Windows), a simple configuration text file, and it works. No Web server or relational database required. It is also easy to translate the interface to the appropriate language for your users.
- its versatility : through its single configuration file, **ELOG** can be made to display an infinity of variants of the *weblog* concept. There are options for what to display, how to display it, what commands are available and to whom, access control, etc. Moreover, a single server can host several *weblogs*, and each *weblog* can be totally different from the rest.

Basic principles of ELOG

https://elog.psi.ch/elog/

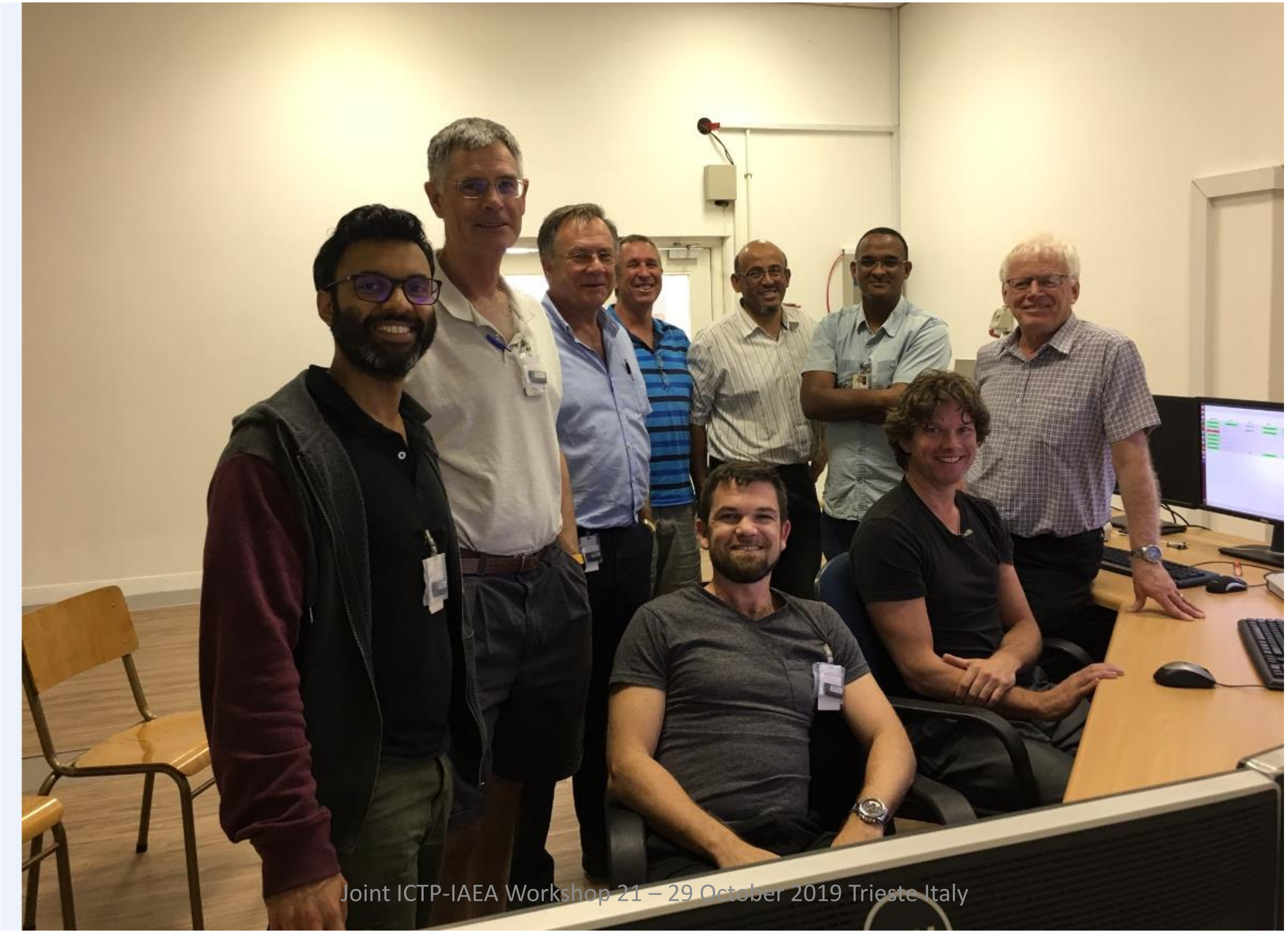
- Web access
  - Reachable from any computer with Web Browser
  - Monolithic C(++) program
    - Faster than interpreted languages
    - Needs less memory, runs nicely on Raspberry PI
    - Does not depend on Web servers
    - No dependency of external libraries (except SSL and Kerberos)
    - Simple to compile and install
  - Recent extensions in JavaScript
- "Designed by user"
  - Only contains features that are needed
  - (Most) needed features are contained
- Configurable
  - Can be electronic logbook, discussion forum, bug tracker, …
  - Huge number of configuration options
  - Some will be covered in this seminar

Beam statistics of the tandetron accelerator

Tandetron Accelerator

STATISTICS	HOURS	Percentage of Calendar time			Financial year
	Sep-2019		2019	2018	2019/20
BEAM SUPPLIED	**607.06**	**84.3**	**75.5**	**21.1**	**83.7**
Beam available	161.28	**22.4**	**27.5**	**11.6**	**36.0**
Beam on target	445.78	**61.9**	**48.0**	**9.4**	**47.7**
to experimental physics	**607.06**	**84.3**	**75.5**	**21.1**	**83.7**
Environment physics	0.00	**0.0**	**0.0**	**0.0**	**0.0**
Material science	286.56	**39.8**	**39.4**	**10.1**	**48.1**
Nuclear microprobe	320.50	**44.5**	**36.0**	**11.0**	**35.6**
Macro pixe	0.00	**0.0**	**0.0**	**0.0**	**0.0**
Nuclear physics	0.00	**0.0**	**0.0**	**0.0**	**0.0**
Experiment Development	0.00	**0.0**	**0.0**	**0.0**	**0.0**
NO BEAM SUPPLIED	**112.89**	**15.7**	**24.5**	**12.3**	**16.3**
Beam development	43.00	**6.0**	**8.5**	**4.3**	**8.9**
Energy changes	23.97	**3.3**	**1.5**	**0.7**	**1.3**
Holidays	0.00	**0.0**	**4.9**	**2.6**	**0.0**
Interruptions	35.50	**4.9**	**2.2**	**4.3**	**2.7**
Maintenance	5.50	**0.8**	**6.7**	**0.3**	**2.4**
Retuning	4.92	**0.7**	**0.7**	**0.1**	**1.0**
Power fail	0.00	**0.0**	**0.0**	**0.0**	**0.0**
ENERGY CHANGES	**Various**		**Accumulated**		
Number	**66**		**104.0**	**13**	**87.0**
Average time (hours)	0.4		**0.9**	**5**	**0.6**

Very happy staff after the first beam from the new Tandetron accelerator (2016)



Thank You